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A DIGITAL COMPUTER TECHNIQUE FOR PREDICTION OF STANDARD MANEUVERS OF SURFACE SHIPS

by

J. Strom-Tejsen

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HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

December 1965 | Report 2130

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FOR

PREDICTION OF STANDARD MANEUVERS OF SURFACE SHIPS

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NOTATION

The system of notation proposed in SNAME, Technical and Research Bulletin No. 1-5, Reference 1,* is used in this report wherever possible. The notation for second and third partial derivatives is taken from Reference 2.

C	Stability criterion
I_x, I_y, I_z	Moments of inertia about x,y,z axes, respectively
K,M,N	Rolling, pitching, and yawing moments, respectively
N_v	Typical static moment derivative; derivative of a moment component with respect to a velocity component $\partial N/\partial v$
N_{vrr}	Typical third partial derivative; partial derivative of a moment with respect to a velocity component and to an angular velocity component $\partial^3 N/\partial v \partial r^2$
$N_{\dot{v}}$	Typical moment of inertia coefficient; derivative of a moment component with respect to an acceleration component $\partial N/\partial \dot{v}$
LBP	Ship length between perpendiculars (used as a characteristic length of body for nondimensionalizing purpose)
m	Mass of body
n_t, n_{t_1}	Propeller revolutions per second at time t and t_1, respectively.
p,q,r	Angular velocities of roll, pitch, and yaw, respectively
$\dot{p}, \dot{q}, \dot{r}$	Angular accelerations of roll, pitch, and yaw, respectively
rate	Rate of deflection of rudder or other control surface
R_t	Resistance
T	Propeller thrust
t	Thrust deduction coefficient
t, Δt	Time and time interval, respectively

*References are listed on page 78

t_{lag}	Time lag in control surface system
$\vec{U}$	Velocity of origin of body axes relative to fluid
u, v, w	Longitudinal, transverse, and normal components, respectively, of the velocity of the origin of body axes relative to fluid
u_1	Velocity in initial equilibrium condition: straight ahead motion at constant speed with rudder amidships
Δu	$u-u_1$
$\dot{u}, \dot{v}, \dot{w}$	Longitudinal, transverse, and normal components, respectively of the acceleration of the origin of body axes relative to fluid
X, Y, Z	Longitudinal, lateral, and normal components, respectively, of hydrodynamic force on body
Y_r	Typical rotary force derivative; derivative of a force component with respect to an angular velocity component $\partial Y/\partial r$
$Y_{r\delta\delta}$	Typical third partial derivative; partial derivative of a force with respect to an angular velocity component and to a rudder deflection $\partial^3 Y/\partial r \partial \delta^2$
$Y_{\dot{r}}$	Typical inertia coefficient; derivative of a force component with respect to an angular acceleration component $\partial Y/\partial \dot{r}$
x, y, z	Body axes fixed in ship; x, y, and z positive forward, starboard, and downwards, respectively. Origin of axes system not necessarily at center of gravity
x_G, y_G, z_G	Coordinates of center of mass relative to body axes
x_0, y_0, z_0	Coordinates relative to the fixed earth axes
x_{00}, y_{00}, z_{00}	Coordinates of origin of body axes relative to the fixed earth axes
Q_t, Q_{t_1}	Propeller torque at a time t and t_1, respectively
β	Angle of drift
δ	Angular displacement of a control surface, normally the rudder angle
ϕ, θ, ψ	Angles of roll, pitch, and yaw, respectively
ρ	Mass density

$\sigma_1, \sigma_2, \sigma_3$ Roots of stability equation

A prime (') applied after the symbol of a quantity indicates the nondimensional form of the quantity. The nondimensional expressions follow SNAME nomenclature, Reference 1.

ABSTRACT

This report presents a computer program for the solution of a mathematical model representing the motion of a surface ship, giving predictions of steering and maneuvering qualities. The nonlinear mathematical model based on a third-order Taylor expansion of forces and moments in the equations of motion is reviewed. The hydrodynamic force and moment derivatives representing the input to the program can be obtained from present captive model testing techniques. Any motion of a surface ship including tight maneuvers and loop phenomenon recognized in the spiral maneuver for a directionally unstable ship should be accurately predictable. The computer program, which gives predictions for the "Standard Maneuvers," turning circles, zig-zag, and spiral maneuver, is described, and results of sample calculations are included. Instructions for preparation of input data for the program, samples of the computer results, and the FORTRAN listing of the computer program are also given.

ADMINISTRATIVE INFORMATION

The mathematical model and associated computer technique presented by the author should be considered as a proposal and not the current standard for the David Taylor Model Basin.

INTRODUCTION

A continuous growth in speed and size of surface ships, an increasing density of traffic on sea routes, and the development of sophisticated control systems for steering and maneuvering are some of the factors which have stimulated the quest for precisely establishing controllability qualities inherent in a surface ship design. As a result the number of ships for which model steering and maneuvering trials are requested and carried out during full-scale trials is increasing.

The time has passed when a turning circle trial was considered sufficient for a determination of handling qualities. Today it is generally recognized that several types of maneuvers should be known in order to evaluate the different modes of performance of the ship such as steering, maneuvering, and turning. A set of trials consisting of a 35-deg turning circle, the 20-20 deg zig-zag, and the spiral maneuver have been proposed for this purpose.[3] These maneuvers are subsequently referred to as the "Standard Maneuvers."

An adherence to these "Standard Maneuvers" in both model test and full-scale trials should make it feasible to establish criteria for steering, maneuvering, and turning, and in the future to evaluate precisely these qualities of ship designs. Another advantage of using "Standard Maneuvers" as basis for criteria is that the evaluation of ship performances can be based on a language that is common to operators as well as to designers and experimenters.

Different testing techniques are in use at model basins for establishing the steering and maneuvering qualities of a ship design. By far the most instructive are based on free-running models, the performance of which are obtained, for example, by a direct execution of the "Standard Maneuvers" in model scale. Despite obvious advantages such as direct modeling of maneuvers, the free-running model technique may present difficulties because of troublesome scaling laws, which hardly can be taken into account in this technique.

The technique advocated in this report utilizes captive model testing for the measurement of hydrodynamic derivatives with a successive

prediction of the "Standard Maneuvers" obtained from a solution of the equations of motion by means of a digital computer or an analog computer setup.

Captive model tests are performed by means of test facilities such as the rotating arm, oscillators, and the planar motion mechanism. They have in the past been adopted primarily for the measurement of the linear hydrodynamic force and moment derivatives necessary for establishing the inherent directional stability of a ship design. Furthermore, the hydrodynamic force and moment derivatives have been used in combination with the linearized equations of motion for analyzing the turning ability of stable ships in the linear range. However, the linear theory would not in general be applicable for predictions of the "Standard Maneuvers", as it fails to predict accurately the tight maneuvers that most ships are capable of performing, and it cannot predict the maneuvers of unstable ships.

If the loop phenomenon (recognized in the spiral maneuver for unstable ships) or the characteristics of tight maneuvers have to be accurately reconstructed analytically, it is necessary to utilize equations of motion expanded to include significant nonlinear terms in the Taylor expansion of forces and moments. Such a nonlinear mathematical model has recently been presented by Abkowitz.[4]

Chislett and Strøm-Tejsen[5,6] have adopted the nonlinear mathematical model and programmed the equations for a digital computer. On the basis of linear and nonlinear hydrodynamic derivatives obtained by planar motion mechanism tests, they have computed predictions for the "Standard Maneuvers" and demonstrated the accuracy with which maneuvers can be predicted in this fashion.

The captive model testing technique has an obvious disadvantage in the fact that no direct display of the ship maneuvers is obtained from the model test. If such a display, however, can be obtained accurately using computer programs or analog setups, this disadvantage is considered of minor importance. The advantages in the technique are numerous; in particular, it allows the experimenter to take scaling laws into proper account and, in a specific ship design, gives him a direct insight into the factors which can be blamed for particular performance qualities.

The nonlinear mathematical model presented by Abkowitz[4] is outlined in the text which follows. The equations have been solved on a digital computer programmed in FORTRAN for the IBM 7090 at TMB. The program gives a prediction of the "Standard Maneuvers" for surface ships on the basis of hydrodynamic force and moment derivatives obtained from captive model tests. The computer program, designated as Applied Mathematics Laboratory (AML) Problem XPMC, is outlined and data preparation, result sheets, and graphs, etc. are described in this report. Included also are the results of some sample calculations, which demonstrate the usage of the computer program and its ability to give detailed information with respect to ship maneuvers. The sample calculations are primarily based on hydrodynamic derivatives for the MARINER hull form published in Reference 5.

The appendices include instructions for the preparation of input data and the FORTRAN listing of the program.

MATHEMATICAL MODEL

The derivation of a nonlinear mathematical model representing the steering and maneuvering of a surface ship is given by Abkowitz.[4] A similar formulation has been used as the basis for the numerical computation in the present computer program. For the sake of completeness of presentation, the development of the Abkowitz mathematical model is outlined briefly; a detailed discussion can be found in Reference 4.

EQUATIONS OF MOTION FOR A SHIP MOVING IN THE HORIZONTAL PLANE

A general form of the equations of motion for a body, which is allowed to move in all the six degrees of freedom, is obtained with the coordinate axis system fixed in the body parallel with the principal axes of inertia, but with an arbitrary origin not necessarily at the center of gravity. For this case the equations are* (see, e.g., References 1 and 4)

$$\begin{aligned}
X &= m\left[\dot{u}+qw-rv-x_G(q^2+r^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})\right]\\
Y &= m\left[\dot{v}+ru-pw-y_G(r^2+p^2)+z_G(qr-\dot{p})+x_G(qp+\dot{r})\right]\\
Z &= m\left[\dot{w}+pv-qu-z_G(p^2+q^2)+x_G(rp-\dot{q})+y_G(rq+\dot{p})\right]\\
K &= I_x\dot{p}+(I_z-I_y)qr+m\left[y_G(\dot{w}+pv-qu)-z_G(\dot{v}+ru-pw)\right]\\
M &= I_y\dot{q}+(I_x-I_z)rp+m\left[z_G(\dot{u}+qw-rv)-x_G(\dot{w}+pv-qu)\right]\\
N &= I_z\dot{r}+(I_y-I_x)pq+m\left[x_G(\dot{v}+ru-pw)-y_G(\dot{u}+qw-rv)\right]
\end{aligned}\qquad(1)$$

where the left-hand side represents the forces and moments along the coordinate axes and the right hand side shows the corresponding dynamic response terms.

*The equations are developed assuming the mass of the body as being constant in time, which can be considered true for most ships.

When dealing with steering and maneuvering of surface ships, the primary motions can be considered to take place in the horizontal plane, and vertical motions can be neglected. Further, choosing an axis system in the plane of symmetry of the body and assuming that the center of gravity lies in the centerline plane and, therefore, $y_G=0$, the equations of motion for a ship moving in the horizontal plane become

$$X = m\left[\dot{u}-rv-x_G r^2+z_G pr\right]$$

$$Y = m\left[\dot{v}+ru-z_G\dot{p}+x_G\dot{r}\right]$$

$$K = I_x\dot{p}-m\cdot z_G(\dot{v}+ru)$$

$$N = I_z\dot{r}+m\cdot x_G(\dot{v}+ru)$$

In the following treatment, rolling and heel of the ship has been neglected, since they are felt to have little influence on steering and maneuvering, with the possible exception of fast warships, which heel appreciably in turns. The equations for steering and maneuvering of a surface ship thus reduce to

$$X = m\left[\dot{u}-rv-x_G r^2\right]$$

$$Y = m\left[\dot{v}+ru+x_G\dot{r}\right]$$

$$N = I_z\dot{r}+m\cdot x_G(\dot{v}+ru)$$

TAYLOR EXPANSION OF FORCES AND MOMENTS

The forces and moments on the left-hand side of the equations of motion can be expressed as functions of properties of the body, properties of the fluid, and properties of the motion. When considering a specific hull form and using the generally accepted scaling laws, the forces and

moments may be considered as functions of the motion and orientation parameters only. When dealing with steering and maneuvering, they are also considered as functions of the deflection δ of control surfaces (rudder):

$$\left.\begin{matrix}\text{Force}\\ \text{Moment}\end{matrix}\right\} = f(\text{properties of motion, rudder deflection})$$

$$= f(\underbrace{x_o, y_o, z_o, \phi, \theta, \psi}_{\text{orientation parameters}}, \underbrace{u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}}_{\text{motion parameters}}, \underbrace{\delta, \dot{\delta}, \ddot{\delta}}_{\text{control surface parameters}}, \text{etc.})$$

When considering motion in an unrestricted horizontal plane, it is clear that no forces or moments are exerted on the ship due to a change in orientation, and the forces and moment will then only be functions of the three degrees of freedom motion parameters and the rudder deflection:

$$\left.\begin{matrix}X\\ Y\\ N\end{matrix}\right\} = f(u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta, \dot{\delta}, \ddot{\delta}, \text{etc.})$$

In the following treatment, it is further assumed that the control forces and moments produced by a deflection of the control surface (rudder) are due to the deflection δ only, while forces and moments produced on the ship as a result of $\dot{\delta}$ and $\ddot{\delta}$ are negligible.*

The functions describing the forces and moments can be developed into a useful form for analysis purposes by the use of the Taylor expansion of a function of several variables. The forces and moments can thus be expressed to any desired degree of accuracy by considering sufficient terms

---

*The variables $\dot{\delta}$ and $\ddot{\delta}$ are considered negligible in the treatment of ship motions, but they are not necessarily negligible, if determining the forces on the rudder itself; e.g., the torque on the rudder stock during a maneuver.

in the expansion. If the expansion is limited to the first order terms, the well-known linearized expansion will be obtained.

If straight ahead motion at constant speed with rudder amidships is chosen as the initial equilibrium condition, the linearized expansion of the forces and moment (Equation (4)) becomes

$$X = X_* + X_u \Delta u + X_v v + X_r r + X_{\dot u} \dot u + X_{\dot v} \dot v + X_{\dot r} \dot r + X_\delta \delta \quad (5)$$

where $\Delta u = (u - u_1)$, with similar expressions for Y and N.

Similarly, the Taylor expansion, including terms up to third order, becomes

$$\begin{aligned} X = X_* &+ \left[X_u \Delta u + X_v v + X_r r + X_{\dot u} \dot u + X_{\dot v} \dot v + X_{\dot r} \dot r + X_\delta \delta \right] \\ &+ \frac{1}{2!} \Big[X_{uu} \Delta u^2 + X_{vv} v^2 + \;\ldots\ldots\; X_{\delta\delta} \delta^2 \; + \\ &\qquad 2 \cdot X_{uv} \Delta u \cdot v + 2 \cdot X_{ur} \Delta u \cdot r + \;\ldots\ldots\; + 2 \cdot X_{\dot r \delta} \dot r \delta \Big] \\ &+ \frac{1}{3!} \Big[X_{uuu} \Delta u^3 + X_{vvv} v^3 + \;\ldots\ldots\; + X_{\delta\delta\delta} \delta^3 \; + \\ &\qquad 3 \cdot X_{uuv} \Delta u^2 v + 3 \cdot X_{uur} \Delta u^2 r + \;\ldots\ldots\; + 3 \cdot X_{\dot r \delta\delta} \dot r \delta^2 + \\ &\qquad 6 \cdot X_{uvr} \Delta u \cdot vr + 6 \cdot X_{uv\dot u} \Delta u \cdot u \dot v + \;\ldots\ldots\; + 6 \cdot X_{\dot v \dot r \delta} \dot v \dot r \delta \Big] \end{aligned} \quad (6)$$

with similar expressions for Y and N.

LINEAR MATHEMATICAL MODEL FOR STEERING AND MANEUVERING

Equating the linearized expansion, Equation (5), with the dynamic response terms given on the right-hand side of the equations of motion, Equations (3), and neglecting dynamic responce of second-order smallness in the same way as second-order terms have been neglected in the force and moment expansions, the linearized equations of motion for steering and maneuvering are obtained

$$X_* + X_u \Delta u + X_v v + X_r r + X_{\dot u}\dot u + X_{\dot v}\dot v + X_{\dot r}\dot r + X_\delta \delta = m\dot u$$

$$Y_* + Y_u \Delta u + Y_v v + Y_r r + Y_{\dot u}\dot u + Y_{\dot v}\dot v + Y_{\dot r}\dot r + Y_\delta \delta = m(\dot v + r u_1 + x_G \dot r) \quad (7)$$

$$N_* + N_u \Delta u + N_v v + N_r r + N_{\dot u}\dot u + N_{\dot v}\dot v + N_{\dot r}\dot r + N_\delta \delta = I_z \dot r + m x_G(\dot v + r u_1)$$

The derivatives X_v, $X_{\dot v}$, X_r, $X_{\dot r}$, and X_δ are all zero for any ship or body with symmetrical shape port and starboard.* As a consequence, Y_u, $Y_{\dot u}$, N_u and $N_{\dot u}$ must also be zero.[4]

With the terms on the right-hand side of the equations brought over to the left side and combined with similar terms, the linear mathematical model for the steering and maneuvering of a surface ship finally becomes

$$(X_{\dot u}-m)\cdot\dot u + X_u \Delta u = 0$$

$$(Y_{\dot v}-m)\cdot\dot v + Y_v v + (Y_{\dot r}-m x_G)\cdot\dot r + (Y_r - m u_1)\cdot r + Y_\delta \delta = 0 \quad (8)$$

$$(N_{\dot v}-m x_G)\dot v + N_v v + (N_{\dot r}-I_z)\cdot\dot r + (N_r - m x_G u_1) r + N_\delta \delta = 0$$

On the basis of the linear model, Equations (8), the well-known criterion for dynamic stability in straight line motion can be evaluated as

$$C = Y_v(N_r - m x_G u_1) - N_v(Y_r - m u_1) > 0 \quad (9)$$

For a dynamically stable ship, the model can furthermore be applied to predict maneuvers as long as only small rudder deflections and small deviations from the original straight line motion are considered. The limitations of the model are, however, obvious from the fact that no speed loss is indicated.

---

*This is one of the advantages by choosing axis systems in the plane of symmetry of the body.

NONLINEAR MATHEMATICAL MODEL

To obtain realistic predictions of maneuvers such as tight turns for large rudder angles and to predict the performance of a dynamically unstable ship, it becomes necessary to develop and solve a nonlinear mathematical model, which includes higher order terms in the Taylor expansion of forces and moments.

The nonlinear mathematical model used as a basis for the computer program has been based on a Taylor expansion of forces and moments including terms of up to third order; see Equations (6). The inclusion of terms higher than third order was not considered to increase the accuracy of prediction significantly. Furthermore, practical limitations of measurement techniques and the state of refinement of present theory did not justify the inclusion of higher terms.

Symmetry considerations demonstrate that the X-equation should be an even function of the parameters v, r, δ, $\dot{v}$, and $\dot{r}$; similarly, the Y- and N-equations are odd functions of the same parameters. Consequently, odd terms in v, r, δ, $\dot{v}$, and $\dot{r}$ have been eliminated from the X-equation, and even terms in the same parameters from the Y- and N-equations. An alternative solution would have been to introduce absolute values of the parameters v, r, δ, $\dot{v}$, and $\dot{r}$ into the equations, but this was considered less attractive.

As a further consequence of the body symmetry, Y_u, Y_{uu}, Y_{uuu}, $Y_{\dot{u}}$ and corresponding derivatives in the moment equation N_u, N_{uu}, N_{uuu}, $N_{\dot{u}}$ are all zero.

An unsymmetrical force (for instance, the side force from a single propeller) has been taken into account by constant terms Y_* and N_* in the Taylor expansion. An unsymmetrical side force has been considered a function of speed, and terms Y_{*u}, Y_{*uu}, N_{*u}, N_{*uu} have consequently been introduced into the mathematical model to facilitate that changes of side force with speed are taken into account.*

The nonlinear equations can be reduced further by considering the nature of the acceleration forces. Abkowitz states,[4] that no second or higher order acceleration terms can be expected. This is based on the assumption that there is no significant interaction between viscous and inertia properties of the fluid and that acceleration forces calculated from potential theory give only linear terms when applied to submerged bodies.

Abkowitz further reasons that terms representing cross-coupling between acceleration and velocity parameters are zero or negligibly small for reasons similar to those just given.

The validity of these basic considerations of Abkowitz' has been verified by the experimental measurements reported in Reference 5.

Equating the nonlinear Taylor expansion, Equations (6), with dynamic response terms, Equations (3), and taking the above considerations into account, the nonlinear equations of motion finally become

$$\text{X-Equation:}\quad (m-X_{\dot{u}})\dot{u} = f_1(u,v,r,\delta)$$

$$\text{Y-Equation:}\quad (m-Y_{\dot{v}})\dot{v} + (mx_G-Y_{\dot{r}})\dot{r} = f_2(u,v,r,\delta) \qquad (10)$$

*If an unsymmetrical force should turn out to be a function of other parameters than speed, this unsymmetry could easily be introduced into the present mathematical model. It would have been more difficult to do this if absolute values of the parameters has been applied.

$$\text{N-Equation:} \quad (mx_G - N_{\dot v})\dot v + (I_z - N_{\dot r})\dot r = f_3(u,v,r,\delta) \tag{10 cont'd}$$

where

$$
\begin{aligned}
f_1(u,v,r,\delta) = {} & X_* + X_u\Delta u + \tfrac{1}{2}X_{uu}\Delta u^2 + \tfrac{1}{6}X_{uuu}\Delta u^3 + \\
& \tfrac{1}{2}X_{vv}v^2 + (\tfrac{1}{2}X_{rr} + mx_G)r^2 + \tfrac{1}{2}X_{\delta\delta}\delta^2 + \tfrac{1}{2}X_{vvu}v^2\Delta u + \tfrac{1}{2}X_{rru}r^2\Delta u + \tfrac{1}{2}X_{\delta\delta u}\delta^2\Delta u + \\
& (X_{vr} + m)vr + X_{v\delta}v\delta + X_{r\delta}r\delta + X_{vru}vr\Delta u + X_{v\delta u}v\delta\Delta u + X_{r\delta u}r\delta\Delta u
\end{aligned}
$$

$$
\begin{aligned}
f_2(u,v,r,\delta) = {} & Y_* + Y_{*u}\Delta u + Y_{*uu}\Delta u^2 + \\
& Y_v v \quad + \tfrac{1}{6}Y_{vvv}v^3 + \tfrac{1}{2}Y_{vrr}vr^2 + \tfrac{1}{2}Y_{v\delta\delta}v\delta^2 + Y_{vu}v\Delta u + \tfrac{1}{2}Y_{vuu}v\Delta u^2 + \\
& (Y_r - mu)r \quad + \tfrac{1}{6}Y_{rrr}r^3 + \tfrac{1}{2}Y_{rvv}rv^2 + \tfrac{1}{2}Y_{r\delta\delta}r\delta^2 + Y_{ru}r\Delta u + \tfrac{1}{2}Y_{ruu}r\Delta u^2 + \\
& Y_\delta\delta \quad + \tfrac{1}{6}Y_{\delta\delta\delta}\delta^3 + \tfrac{1}{2}Y_{\delta vv}\delta v^2 + \tfrac{1}{2}Y_{\delta rr}\delta r^2 + Y_{\delta u}\delta\Delta u + \tfrac{1}{2}Y_{\delta uu}\delta\Delta u^2 + Y_{vr\delta}vr\delta
\end{aligned}
$$

$$
\begin{aligned}
f_3(u,v,r,\delta) = {} & N_* + N_{*u}\Delta u + N_{*uu}\Delta u^2 + \\
& N_v v \quad + \tfrac{1}{6}N_{vvv}v^3 + \tfrac{1}{2}N_{vrr}vr^2 + \tfrac{1}{2}N_{v\delta\delta}v\delta^2 + N_{vu}v\Delta u + \tfrac{1}{2}N_{vuu}v\Delta u^2 + \\
& (N_r - mx_G u)r + \tfrac{1}{6}N_{rrr}r^3 + \tfrac{1}{2}N_{rvv}rv^2 + \tfrac{1}{2}N_{r\delta\delta}r\delta^2 + N_{ru}r\Delta u + \tfrac{1}{2}N_{ruu}r\Delta u^2 + \\
& N_\delta\delta \quad + \tfrac{1}{6}N_{\delta\delta\delta}\delta^3 + \tfrac{1}{2}N_{\delta vv}\delta v^2 + \tfrac{1}{2}N_{\delta rr}\delta r^2 + N_{\delta u}\delta\Delta u + \tfrac{1}{2}N_{\delta uu}\delta\Delta u^2 + N_{vr\delta}vr\delta
\end{aligned}
$$

PRINCIPLES FOR SOLUTION OF MATHEMATICAL MODEL USING DIGITAL COMPUTER

METHOD OF NUMERICAL SOLUTION

The mathematical model, Equations (10), can be solved with respect to the accelerations $\dot u$, $\dot v$, and $\dot r$, which become

$$\dot u = \frac{f_1(u,v,r,\delta)}{(m - X_{\dot u})}$$

$$\dot v = \frac{(I_z - N_{\dot r})\, f_2(u,v,r,\delta) - (mx_G - Y_{\dot r})\, f_3(u,v,r,\delta)}{(m - Y_{\dot v})(I_z - N_{\dot r}) - (mx_G - N_{\dot v})(mx_G - Y_{\dot r})} \tag{11}$$

$$\dot{r} = \frac{(m-Y_{\dot{v}})\ f_3(u,v,r,\delta) - (mx_G-N_{\dot{v}})\ f_2(u,v,r,\delta)}{(m-Y_{\dot{v}})(I_z-N_{\dot{r}}) - (mx_G-N_{\dot{v}})\ (mx_G-Y_{\dot{r}})} \tag{11 cont'd}$$

These solutions can be rewritten in the form

$$\begin{aligned} \frac{du}{dt} &= g_1\left[t,u(t),v(t),r(t),\delta(t)\right] \\ \frac{dv}{dt} &= g_2\left[t,u(t),v(t),r(t),\delta(t)\right] \\ \frac{dr}{dt} &= g_3\left[t,u(t),v(t),r(t),\delta(t)\right] \end{aligned} \tag{12}$$

It is seen that the mathematical model has been reduced to a set of three first-order differential equations. An approximate numerical solution for this type of equations is readily obtained on a digital computer. The process in the numerical solution is that the values of u, v, and r at time $t+\Delta t$ are obtained from knowledge of the values of u, v, r, and δ at time t.

A simple first-order method has been applied in the computer program; the values at time $t+\Delta t$ are obtained simply by the first-order Taylor series expansion

$$\begin{aligned} u(t+\Delta t) &= u(t) + \Delta t\cdot\dot{u}(t) \\ v(t+\Delta t) &= v(t) + \Delta t\cdot\dot{v}(t) \\ r(t+\Delta t) &= r(t) + \Delta t\cdot\dot{r}(t) \end{aligned} \tag{13}$$

This method is found to give adequate accuracy for the present type of differential equations, because of the fact that the accelerations $\dot{u}$, $\dot{v}$, and $\dot{r}$ vary only slowly with time. This is due to the large mass and inertia of a ship compared to the relatively small forces and moments produced by its control surfaces.

Furthermore, digital computers enable long repetitive calculations to be made fast and accurately, and any desired accuracy of the solutions can be obtained using small time intervals Δt.

CALCULATION PROCEDURE FOR PREDICTION OF TRAJECTORY

So far, the mathematical model has been developed in dimensional form. The development has on the other hand been completely general, and the equations are equally valid in the nondimensional form.*

In the computer program, the mathematical model has been adopted in its nondimensional form. To describe the calculation of a trajectory in dimensional form on the basis of the nondimensional equations, the non-dimensionalized form of a given quantity will be indicated by the prime of that quantity in the following discussion.

Assuming that a full set of nondimensional hydrodynamic coefficients (X_u', X_{uu}', Y_v', N_r', etc.) is available and that the rudder deflection δ is defined as a function of time, the first step in the calculation of the trajectory of a ship maneuver would be to define the initial condition, i.e., set the nondimensional values

$$
\begin{aligned}
u(t)' &= u(t)/u(t) \\
v(t)' &= v(t)/u(t) \\
r(t)' &= r(t)/(u(t)/LBP) \\
\delta(t)' &= \delta(t)
\end{aligned}
\qquad (14)
$$

at time t=0. Having done this, the nondimensional accelerations $\dot{u}'$, $\dot{v}'$, and $\dot{r}'$ can be calculated from equations (11), and the corresponding accelerations in dimensional form from

*The velocity used for nondimensionalization should be the velocity at any time, t rather than the initial velocity.

$$\dot{u}(t) = \dot{u}(t)' \cdot (u(t)^2/LBP)$$
$$\dot{v}(t) = \dot{v}(t)' \cdot (u(t)^2/LBP) \quad (15)$$
$$\dot{r}(t) = \dot{r}(t)' \cdot (u(t)^2/LBP^2)$$

The new velocities in dimensional form at time $t=\Delta t$ can be obtained from Equations (13) and the corresponding nondimensional values from Equations (14). The process is then repeated using the new values for u', v', r', and δ' in Equations (11), and so on. The values of the velocities at a time t are thus obtained from

$$u(t) = u(0) + \sum_{\tau=0}^{t-\Delta t} \dot{u}(\tau) \cdot \Delta t$$
$$v(t) = v(0) + \sum_{\tau=0}^{t-\Delta t} \dot{v}(\tau) \cdot \Delta t \quad (16)$$
$$r(t) = r(0) + \sum_{\tau=0}^{t-\Delta t} \dot{r}(\tau) \cdot \Delta t$$

where u(0), v(0), and r(0) are the values of u, v, and r at t=0, and τ represents intermediate values of time (between time, 0 and time, $t-\Delta t$) at which the accelerations $\dot{u}(t)$, $\dot{v}(t)$, and $\dot{r}(t)$ are determined.

The instantaneous coordinates of the path of the origin of the ship $x_{o0}(t)$ and $y_{o0}(t)$ relative to the fixed earth axes, the instantaneous radius of curvature R(t), angle of yaw $\psi(t)$, etc., can be obtained similarly from the velocities by using the formulas

$$\psi(t) = \psi(0) + \sum_{\tau=0}^{t-\Delta t} r(\tau) \cdot \Delta t$$
$$(17)$$
$$x_{o0}(t) = x_{o0}(0) + \sum_{\tau=0}^{t-\Delta t} \left[v(\tau) \cdot \cos\psi(\tau) + (u(\tau) - u(0)) \cdot \sin\psi(\tau) \right] \cdot \Delta t$$

$$y_{o0}(t) = y_{o0}(0) + \sum_{\tau=0}^{t-\Delta t}\left[(u(\tau)-u(0))\cdot\cos\psi(\tau) - v(\tau)\cdot\sin\psi(\tau)\right]\cdot\Delta t$$

$$R(t) = \frac{\sqrt{(u(t)+u(0))^2 + v(t)^2}}{r(t)} \qquad (17) \text{ cont'd}$$

The accuracy of the predicted trajectory can be controlled by running the calculation with different values of the time interval Δt. It is found that a high accuracy is easily obtainable, and a time interval of $\Delta t = 1$ sec has been chosen as standard in the computer program.

DEFINITION OF RUDDER DEFLECTION

It is necessary in the calculation of a ship trajectory,as mentioned above, to define the rudder deflection as a function of time. This has been accomplished in the computer program by assuming the rudder to move with a certain constant rate of deflection and assuming a certain timelag between the instant the rudder deflection is ordered, and the instant the rudder begins to move. A rudder deflection up to a certain given angle δ_{const} would be executed in the program as indicated in the following example:

$$\delta(t) = \delta(t_1) \qquad \text{until} \quad t > t_{lag} + t_1$$

$$\text{then } \delta(t) = \delta(t_1) + \text{rate}\cdot(t-t_1-t_{lag}) \qquad \text{until } \delta(t) = \delta_{const}$$

$$\text{then } \delta(t) = \delta_{const}.$$

A rudder function of this type gives a close approximation to the actual time history of a ship's rudder when a certain maneuver is ordered on the bridge, and almost any practical rudder sequence encountered when

considering ship maneuvers can be built up. The zig-zag maneuver can, for example, be built up as follows, using these principles:

$$
\begin{array}{lll}
 & \delta(t) = \delta(t_1) & \text{until } t > t_{lag} + t_1 \\
\text{then} & \delta(t) = \delta(t_1) + \text{rate}\cdot(t - t_{lag} - t_1) & \text{until } \delta(t) = \delta_{const} \\
\text{then} & \delta(t) = \delta_{const} & \text{until } t = t_2 \text{ when } \psi = \delta_{const} \\
\text{then} & \delta(t) = \delta_{const} & \text{until } t > t_{lag} + t_2 \\
\text{then} & \delta(t) = \delta_{const} - \text{rate}\cdot(t - t_{lag} - t_2) & \text{until } \delta(t) = -\delta_{const} \\
\text{then} & \delta(t) = -\delta_{const} & \text{until } t = t_3 \text{ when } \psi = -\delta_{const} \\
\text{then} & \delta(t) = -\delta_{const} & \text{until } t > t_{lag} + t_3 \\
\text{then} & \delta(t) = -\delta_{const} + \text{rate}\cdot(t - t_{lag} - t_3) & \text{until } \delta(t) = \delta_{const} \\
\text{then repeat.} & &
\end{array}
$$

COEFFICIENTS IN MATHEMATICAL MODEL

EXPERIMENTAL TECHNIQUES FOR MEASUREMENT OF COEFFICIENTS

To perform the computations of ship maneuvers, it is necessary to know the various hydrodynamic derivatives (X_u, Y_v, N_{vvr}, etc.) which appear in the mathematical model, Equations (10). These coefficients depend largely upon the ship geometry and design, and in general they differ significantly from one hull form to another. For most of the coefficients, it is necessary to rely on model testing techniques of special nature in order to determine the values for the particular ship form.

The coefficients are by definition partial derivatives of a force or moment with respect to one or more of the motion parameters. To obtain the different coefficients, it is necessary to let the model execute various forced motions and to measure the forces and moments as functions of the

different motion parameters. An example might illustrate this principle. For a model which has been towed at different specific drift angles, corresponding forces Y and moments N have been measured. Figure 1 shows the nondimensional values Y' and N' plotted as a function of the nondimensional side velocity $v'=v/u$. From these measurements, it is now possible to obtain the derivatives with respect to the side velocity v, namely, Y_v, Y_{vvv} as well as N_v and N_{vvv}. The derivatives are related in a simple manner to the coefficients in the third-order polynominals, which give the best curve fitting to the experimental values. Thus, if the third-order polynomials fitted, e.g., by a least squares procedure, are of the form:

$$\begin{aligned} Y' &= a_0 + a_1 \cdot v' + a_3 \cdot v'^3 \\ N' &= b_0 + b_1 \cdot v' + b_3 \cdot v'^3 \end{aligned} \tag{18}$$

then the derivatives would be directly related to the polynom-coefficients as follows:

$$\begin{aligned} Y_v' &= a_1 & \qquad \frac{1}{6} Y_{vvv}' &= a_3 \\ N_v' &= b_1 & \qquad \frac{1}{6} N_{vvv}' &= b_3 . \end{aligned} \tag{19}$$

Different testing facilities such as rotating arm, oscillators, and planar motion mechanism are capable of executing model tests with various types of forced motions. The most versatile instrumentation is probably the planar motion mechanism because any type of motion with respect to which derivatives are desired can be produced by this instrumentation. A detailed discussion of a planar motion mechanism and the technique for measuring the different derivatives for a surface ship is presented in Reference 6. Here it is sufficient to mention that measuring techniques are available, which

in model scale permit measuring the different derivatives appearing in the mathematical model, Equations (10).

CALCULATION OF COEFFICIENTS IN X-EQUATION

Three of the coefficients in the X-equation, X_u, $\frac{1}{2}X_{uu}$, and $\frac{1}{6}X_{uuu}$, are calculated in the computer program on the basis of the results from open-water propeller test and the ship effective horsepower data.

When the ship is sailing straight ahead with constant velocity u_1, the propeller thrust working with the thrust deduction exactly equals the resistance of the ship

$$X = T(1-t) - R_t = 0 \tag{20}$$

This equilibrium condition defines the initial propeller thrust and the corresponding propeller torque and revolutions.

As soon as a maneuver is initiated, this equilibrium condition is disturbed. The X-force, which represents the difference between the propeller thrust and the ship resistance, will vary as a function of the speed. Approximating the X-force by a third-order polynomial,

$$X(u) = a_0 + a_1 \cdot \Delta u + a_2 \cdot \Delta u^2 + a_3 \cdot \Delta u^3$$

where $\Delta u = (u-u_1)$, the derivatives X_*, X_u, $\frac{1}{2}X_{uu}$, $\frac{1}{6}X_{uuu}$ can be obtained directly from the coefficients of the polynomials as follows:

$$X_* = a_0 \sim 0; \quad X_u = a_1; \quad \frac{1}{2}X_{uu} = a_2; \quad \frac{1}{6}X_{uuu} = a_3$$

In the program the actual X-force is computed at the different speed values for which the ship resistance is known from the ship effective horsepower data. The corresponding propeller thrust values are computed using

different assumptions that depend upon the type of engine and the engine setting to be maintained during the maneuver.

The propeller thrust can thus be calculated, either assuming constant propeller revolutions or assuming the propeller torque to vary proportionally to the revolutions in a certain power. If torque is assumed to vary inversely proportional to propeller revolutions, the thrust values corresponding to a turbine power plant capable of maintaining a constant power output would be obtained. If torque is assumed to be constant during the maneuver, the corresponding condition for a Diesel power plant would be obtained.

SCALE EFFECTS

Most of the coefficients to be used in the mathematical model would be obtained from model tests, and in this connection it is reasonable to give some considerations to scale effects in the measurement of the coefficients.

The model tests would be conducted according to Froude's law, hence the Reynolds number would not be satisfied, and the possibility of Reynolds number effects should be recognized.

Tests with airfoils covering a wide range of Reynolds numbers indicate that change of Reynolds number apparently has no systematic effect on the lift-curve slope. However, the variation of maximum lift might be appreciable because separation or flow breakdown occur earlier for the relatively thicker boundary layer around a model body at the lower Reynolds number. These results from airfoil testing can be applied in the present discussion of scale effects, as most of the Y-forces and N-moments would be due to similar lift and circulation effects. Thus, according to the nature of the

Reynolds number effect, scale effects should not be expected for any of the first-order derivatives, e.g., Y_v, Y_r, Y_δ, N_v, N_r, N_δ, etc., which in general only represent lift slope characteristics. In the case of the higher order derivatives, however, the possibility of scale effects should be considered, as it is likely that these coefficients would be influenced if separation or flow breakdown occurred. Normally, higher order derivatives of the motion parameters v and r, for instance Y_{vvv}, Y_{rrr} etc., are determined for relatively small values of v and r corresponding to angles of attack before any separation effect takes place. For this reason, scale effects would probably be negligible also for these coefficients. This is not true for the rudder, as the rudder deflection for which rudder characteristics are measured also will cover the range of rudder breakdown. For the derivatives $Y_{\delta\delta\delta}$ and $N_{\delta\delta\delta}$, in particular, a rational correction for scale effects should be considered.

The maximum lift is sensitive to surface roughness, especially near the leading edge. Thus, model rudders should be finished as smooth as possible in order to operate in a well-defined condition and to obtain repeatable measurements. Similarly, the surface roughness of the full-scale rudder should be taken into consideration and corrected for as part of the above-mentioned correction of rudder derivatives $Y_{\delta\delta\delta}$ and $N_{\delta\delta\delta}$ for Reynolds number effect.

Model tests should be carried out for propeller revolutions corresponding to the ship propulsion point and not to the model propulsion point, which, e.g., normally would have to be applied using free-running, self-propelled models. The propeller slipstream can thus be correctly modeled. This has been found to be very important, as it has a great effect not

only upon the rudder derivatives Y_δ and N_δ, but also upon the hull derivatives Y_v, Y_r, N_v and N_r.

As outlined previously, the coefficients X_u, X_{uu} and X_{uuu} in this computer program are calculated on the basis of the proper ship resistance values and a power assumption corresponding to the engine setting which would be attempted during an actual maneuver. As these coefficients are of prime importance in obtaining the correct speed reduction during a maneuver, it is found that a principal scale effect problem has thus been taken properly into account. This procedure would be contrary to the free-running model technique, where the difference between model and ship resistance would be a serious problem and result in the measurement of a too small speed reduction in model scale.

The foregoing discussion of factors influencing scale effect should indicate that it is possible to take scale effect problems into account in the determination of the different coefficients for the mathematical model. Present experience might be insufficient to introduce a correction for Reynolds number effect as suggested for the rudder derivatives $Y_{\delta\delta\delta}$ and $N_{\delta\delta\delta}$; nevertheless, a correction is thought to be feasible. It is emphasized that this is in contrast to the free-running model technique, where the scale effect problems caused by incorrect propulsion point, Reynolds number effects, etc., would be completely mixed up in the model results, leaving only very little room for introduction of scale effect corrections based on a proper physical understanding of the problem.

VARIATIONS OF COEFFICIENTS WITH SPEED

The computer program has been based on a solution of the mathematical model in nondimensional form; consequently, the coefficients used as input

data to the program should be applied in their corresponding nondimensional form.

The calculation of a full-scale trajectory of a ship maneuver is based on dimensionalizing by the instantaneous forward velocity u(t); see Equations (14) and (15). When a certain speed loss takes place during a maneuver, forces and moments are thus basically considered as being proportional with the instantaneous speed squared, and coefficients such as Y_{vu}, Y_{vuu}, Y_{ru}, Y_{ruu}, $Y_{\delta u}$, $Y_{\delta uu}$, etc., which represent the change of forces and moments with speed, should only reflect the extent to which this proportionality does not hold true.

Measurements of the nondimensional coefficients Y_v', Y_r', N_v', and N_r' carried out for various ship models at different speed values have indicated that these coefficients are largely independent of speed. Thus coefficients Y_{vu}', Y_{vuu}', Y_{ru}', Y_{ruu}', N_{vu}', N_{vuu}', N_{ru}', and N_{ruu}', which should represent the change with speed, are negligible. Consequently, at present it has been found reasonable to eliminate these coefficients in the computer program.

For the rudder derivatives Y_δ' and N_δ', a noteworthy effect has been measured for a change in forward speed especially on ships where the rudder is situated in the propeller slipstream. Apparently, this is due to the fact that the propeller slipstream is nearly constant even for a considerable change of forward speed, because propeller revolutions are kept more or less constant during a maneuver. Thus, the velocity of the inflow to the rudder is not dependent on forward speed alone; consequently, the nondimensional coefficients Y_δ' and N_δ' must vary as a function of forward speed. The coefficients $Y_{\delta u}'$ and $N_{\delta u}'$, which represent the first order change of the rudder derivatives with speed, are for this reason thought to be of

considerable importance, and they should be included in an experimental determination of the various coefficients.

The coefficients $Y_{\delta uu}'$, $N_{\delta uu}'$, representing only the second-order change of Y_δ' and N_δ' with speed, have nevertheless, been considered negligible and eliminated in the program.

The coefficients X_{vvu}', X_{rru}', $X_{\delta\delta u}'$, X_{vru}', $X_{v\delta u}'$, and $X_{\delta ru}'$ in the X-equation, which represent the change of X_{vv}', X_{rr}', $X_{\delta\delta}'$, X_{vr}', $X_{v\delta}'$, and $X_{\delta r}'$ with forward speed, have similarly been omitted from the computer program as they are thought be be of minor importance at least in comparison with the dominating coefficients X_u, X_{uu}, and X_{uuu}.

RESUMÉ OF COEFFICIENTS

The mathematical model developed in Equations (10) include 17 coefficients in the X-equation and 24 coefficients in each of the Y- and N-equations. As mentioned in the previous section, several of the coefficients representing change of nondimensional forces and moments with forward speed have been found negligible and are eliminated in the computer program.

Obviously, coefficients are of varying importance with respect to the accuracy of a prediction, and a classification of the coefficients has been attempted in the summary of the coefficients given in Tables 1-3, pages 25-27.

The tables also show the identifiers that have been used for the coefficients in the computer program as well as nondimensional factors and examples of the numerical values taken from Reference 5. The planar motion mechanism test technique, which could be used to measure the coefficients, is mentioned briefly.

Table 1 - Summary of Coefficients in X-Equation

Variable	X - Equation: Taylor Expansion And Dynamic Response Terms	Identifier in FORTRAN Program (1)	Nondim. Factor	Nondim. Coeff. $\cdot 10^5$ from Example (2)	Relative Importance of Coeff. (3)	Planar Motion Mechanism Test Technique or Calculation Method
$\dot{u}$	$(m-X_{\dot{u}})$	X UDOT	$\frac{1}{2}\rho LBP^3$	840.0	I	Estimated from theory $X_{\dot{u}} \sim -0.05\ m$
Δu	X_u	X U	$\frac{1}{2}\rho LBP^2 u$	-120.0	I	Calculated on the basis of ship
Δu^2	$\frac{1}{2} X_{uu}$	X UU	$\frac{1}{2}\rho LBP^2$	45.0	I	EHP-data and results from open-
Δu^3	$\frac{1}{6} X_{uuu}$	X UUU	$\frac{1}{2}\rho LBP^2/u$	-10.3	I	water propeller test.
v^2	$\frac{1}{2} X_{vv}$	X VV	$\frac{1}{2}\rho LBP^2$	-899.8	MI	Static drift angle test
r^2	$(\frac{1}{2} X_{rr}+mx_G)$	X RR	$\frac{1}{2}\rho LBP^4$	19.0	MI	Pure yaw (angular motion) test
δ^2	$\frac{1}{2} X_{\delta\delta}$	X DD	$\frac{1}{2}\rho LBP^2 u^2$	-94.8	MI	Static drift angle test
$v^2\Delta u$	$\frac{1}{2} X_{vvu}$		$\frac{1}{2}\rho LBP^2/u$			
$r^2\Delta u$	$\frac{1}{2} X_{rru}$		$\frac{1}{2}\rho LBP^4/u$			
$\delta^2\Delta u$	$\frac{1}{2} X_{\delta\delta u}$		$\frac{1}{2}\rho LBP^2 u$			
vr	$(X_{vr}+m)$	X VR	$\frac{1}{2}\rho LBP^3$	798.0	N	Yaw and drift angle test - m is known
$v\delta$	$X_{v\delta}$	X VD	$\frac{1}{2}\rho LBP^2 u$	93.2	N	Static drift angle test
$r\delta$	$X_{r\delta}$	X RD	$\frac{1}{2}\rho LBP^3 u$	0.0	N	Yaw and rudder angle test
$vr\Delta u$	X_{vru}		$\frac{1}{2}\rho LBP^3/u$			
$v\delta\Delta u$	$X_{v\delta u}$		$\frac{1}{2}\rho LBP^2$			
$r\delta\Delta u$	$X_{r\delta u}$		$\frac{1}{2}\rho LBP^3$			
-	X_*	X 0	$\frac{1}{2}\rho LBP^2 u^2$	0.0	N	Static drift angle test

(1) The Fortran program does not include all terms in the mathematical model, Equations (10). Certain coe fficients have been left out, as they have been considered unimportant for the accuracy of the predictions.

(2) The nondimensional coefficients have been taken from Reference 5.

(3) The coefficients have been divided into three grades according to their importance for the accuracy of a prediction. The most important coefficients are indicated by I; coefficients of minor importance by MI; coefficients, which apparently are negligible, by N.

Table 2 - Summary of Coefficients in Y-Equation

Variable	Y - Equation: Taylor Expansion And Dynamic Response Terms	Identifier in FORTRAN Program (1)	Nondim. Factor	Nondim. Coeff. $\cdot 10^5$ from Example (2)	Relative Importance of Coeff. (3)	Planar Motion Mechanism Test Technique or Calculation Method
$\dot{v}$	$(m-Y_{\dot{v}})$	Y VDOT	$\frac{1}{2}\rho\,LBP^3$	1546.0	I	Pure sway (transverse motion) test
$\dot{r}$	$(mx_G-Y_{\dot{r}})$	Y RDOT	$\frac{1}{2}\rho\,LBP^4$	-8.6	I	Pure yaw (angular motion) test
v	Y_v	Y V	$\frac{1}{2}\rho\,LBP^2u$	-1160.4	I	Static drift angle test
v^3	$\frac{1}{6}Y_{vvv}$	Y VVV	$\frac{1}{2}\rho\,LBP^2/u$	-8078.2	MI	Static drift angle test
vr^2	$\frac{1}{2}Y_{vrr}$	Y VRR	$\frac{1}{2}\rho\,LBP^4/u$	0.0	N	Yaw and drift angle test
$v\delta^2$	$\frac{1}{2}Y_{v\delta\delta}$	Y VDD	$\frac{1}{2}\rho\,LBP^2u$	-3.8	N	Static drift angle test
$v\Delta u$	Y_{ru}		$\frac{1}{2}\rho\,LBP^2$			
$v\Delta u^2$	$\frac{1}{2}Y_{vuu}$		$\frac{1}{2}\rho\,LBP^2/u$			
r	(Y_r-mu)	Y R	$\frac{1}{2}\rho\,LBP^3u$	-499.0	I	Pure yaw (angular motion) test
r^3	$\frac{1}{6}Y_{rrr}$	Y RRR	$\frac{1}{2}\rho\,LBP^5/u$	0.0	N	Pure yaw (angular motion) test
rv^2	$\frac{1}{2}Y_{rvv}$	Y RVV	$\frac{1}{2}\rho\,LBP^3/u$	15356.0	I	Yaw and drift angle test
$r\delta^2$	$\frac{1}{2}Y_{r\delta\delta}$	Y RDD	$\frac{1}{2}\rho\,LBP^3u$	0.0	N	Yaw and rudder angle test
$r\Delta u$	Y_{ru}		$\frac{1}{2}\rho\,LBP^3$			
$r\Delta u^2$	$\frac{1}{2}Y_{ruu}$		$\frac{1}{2}\rho\,LBP^3/u$			
δ	Y_δ	Y D	$\frac{1}{2}\rho\,LBP^2u^2$	277.9	I	Static drift angle test
δ^3	$\frac{1}{6}Y_{\delta\delta\delta}$	Y DDD	$\frac{1}{2}\rho\,LBP^2u^2$	-90.0	MI	Static drift angle test
δv^2	$\frac{1}{2}Y_{\delta vv}$	Y DVV	$\frac{1}{2}\rho\,LBP^2$	1199.6	MI	Static drift angle test
δr^2	$\frac{1}{2}Y_{\delta rr}$	Y DRR	$\frac{1}{2}\rho\,LBP^4$	0.0	N	Yaw and rudder angle test
$\delta\Delta u$	$Y_{\delta u}$	Y DU	$\frac{1}{2}\rho\,LBP^2u$	(0.0)	MI	Static drift angle test executed at various speed values
$\delta\Delta u^2$	$\frac{1}{2}Y_{\delta uu}$		$\frac{1}{2}\rho\,LBP^2$			
$vr\delta$	$Y_{vr\delta}$	Y VRD	$\frac{1}{2}\rho\,LBP^3$	0.0	N	Yaw and drift angle test executed at various speed values
-	Y_*	Y O	$\frac{1}{2}\rho\,LBP^2u^2$	-3.6	MI	Static drift angle test
Δu	Y_{*u}	Y OU	$\frac{1}{2}\rho\,LBP^2u$	(0.0)	N	Static drift angle test executed at various speed values
Δu^2	Y_{*uu}		$\frac{1}{2}\rho\,LBP^2$			

(1) The FORTRAN program does not incorporate all terms in the mathematical model, Equations (10). Certain coefficients have been left out, as they have been considered without importance for the accuracy of the predictions.

(2) The nondimensional coefficients have been taken from Reference 5 except values enclosed in parenthesis, for which no data were available.

(3) The coefficients have been divided into three grades according to their importance for the accuracy of a prediction. The most important coefficients, which should be available in order to obtain a prediction, are marked by I; coefficients of minor importance by MI: coefficients which apparently are negligible, by N.

Table 3 - Summary of Coefficients in N-Equation

Variable	N - E q u a t i o n					Planar Motion Mechanism Test Technique or Calculation Method
	Taylor Expansion And Dynamic Response Terms	Identifier in FORTRAN Program (1)	Nondim. Factor	Nondim. Coeff. $\times 10^5$ from Example (2)	Relative Importance of Coeff. (3)	
$\dot{v}$	$(mx_G - N_{\dot{v}})$	N VDOT	$\frac{1}{2}\rho\, LBP^4$	-22.7	I	Pure sway (transverse motion) test
$\dot{r}$	$(I_z - N_{\dot{r}})$	N RDOT	$\frac{1}{2}\rho\, LBP^5$	82.9	I	Pure yaw (angular motion) test
v	N_v	N V	$\frac{1}{2}\rho\, LBP^3 u$	-263.5	I	Static drift angle test
v^3	$\frac{1}{6} N_{vvv}$	N VVV	$\frac{1}{2}\rho\, LBP^3/u$	1636.1	MI	Static drift angle test
vr^2	$\frac{1}{2} N_{vrr}$	N VRR	$\frac{1}{2}\rho\, LBP^5/u$	0.0	N	Yaw and drift angle test
$v\delta^2$	$\frac{1}{2} N_{v\delta\delta}$	N VDD	$\frac{1}{2}\rho\, LBP^3 u$	12.5	N	Static drift angle test
$v\Delta u$	N_{vu}		$\frac{1}{2}\rho\, LBP^3$			
$v\Delta u^2$	$\frac{1}{2} N_{vuu}$		$\frac{1}{2}\rho\, LBP^3/u$			
r	$(N_r - mx_G u)$	N R	$\frac{1}{2}\rho\, LBP^4 u$	-166.0	I	Pure yaw (angular motion) test
r^3	$\frac{1}{6} N_{rrr}$	N RRR	$\frac{1}{2}\rho\, LBP^6/u$	0.0	N	Pure yaw (angular motion) test
rv^2	$\frac{1}{2} N_{rvv}$	N RVV	$\frac{1}{2}\rho\, LBP^4/u$	-5483.0	[illegible]	Yaw and drift angle test
$r\delta^2$	$\frac{1}{2} N_{r\delta\delta}$	N RDD	$\frac{1}{2}\rho\, LBP^4 u$	0 0	N	Yaw and rudder angle test
$r\Delta u$	N_{ru}		$\frac{1}{2}\rho\, LBP^4$			
$r\Delta u^2$	$\frac{1}{2} N_{ruu}$		$\frac{1}{2}\rho\, LBP^4/u$			
δ	N_δ	N D	$\frac{1}{2}\rho\, LBP^3 u^2$	-138.8	I	Static drift angle test
δ^3	$\frac{1}{6} N_{\delta\delta\delta}$	N DDD	$\frac{1}{2}\rho\, LBP^3 u^2$	45.0	MI	Static drift angle test
δv^2	$\frac{1}{2} N_{\delta vv}$	N DVV	$\frac{1}{2}\rho\, LBP^3$	-489.0	MI	Static drift angle test
δr^2	$\frac{1}{2} N_{\delta rr}$	N DRR	$\frac{1}{2}\rho\, LBP^4 u$	0.0	N	Yaw and rudder angle test
$\delta\Delta u$	$N_{\delta u}$	N DU	$\frac{1}{2}\rho\, LBP^3 u$	(0.0)	MI	Static drift angle test executed at various speed values
$\delta\Delta u^2$	$\frac{1}{2} N_{\delta uu}$		$\frac{1}{2}\rho\, LBP^3$			
$vr\delta$	$N_{vr\delta}$	N VRD	$\frac{1}{2}\rho\, LBP^4$	0.0	N	Yaw and drift angle test executed for various speed values
-	N_0	N O	$\frac{1}{2}\rho\, LBP^3 u^2$	2.8	MI	Static drift angle test
Δu	N_{0u}	N OU	$\frac{1}{2}\rho\, LBP^3 u$	(0.0)	N	Static drift angle test executed at various speed values
Δu^2	N_{0uu}		$\frac{1}{2}\rho\, LBP^3$			

(1) The FORTRAN program does not incorporate all terms in the mathematical model, Equations (10). Certain coefficients have been left out, as they have been considered without importance for the accuracy of the predictions.

(2) The nondimensional coefficients have been taken from Reference 5 except values enclosed in parenthesis, for which no data were available.

(3) The coefficients have been divided into three grades according to their importance for the accuracy of a prediction. The most important coefficients, which should be available in order to obtain a prediction, are marked by I; coefficients of minor importance by MI; coefficients, which apparently are negligible, by N.

COMPUTER PROGRAM FOR PREDICTION OF STANDARD MANEUVERS

The solution of the mathematical model for steering and maneuvering has been programmed in the FORTRAN II language available for the IBM 7090 computer at TMB. The program is designated AML Problem XPMC. The FORTRAN listing of the computer program is included in Appendix C of this report.

INPUT DATA

Data forms have been worked out to help in the accurate preparation of input data for the computer program. An example of the data forms is given in Appendix A, and the following discussion of the input data refers to this example.

The input data consist of two parts: (1) Specification data, page 52 and (2) Ship data, pages 53-56 .

Specification Data

The specification data describe the maneuvers which should be predicted at the execution of the program. Four different types of calculations can be specified and carried out by the program:

1. Calculation of the turning circle parameters as defined in Figure 2. The parameters are calculated for a series of different rudder deflections, which should be specified in the data form.
2. Calculation of the turning circle trajectory for a certain rudder deflection. Parameters such as advance, transfer, speed, heading angle, angular velocity, and drift angle are presented on a time basis for each 10 sec until a 450-deg turn has been executed. The turning circle calculation can be specified for several rudder deflections at each execution of the program.

3. Calculation of the zig-zag maneuver as defined diagrammatically in Figure 3. The same parameters as mentioned above for the turning circle calculation are presented on the basis of a time interval of 10 sec. The calculation of the zig-zag maneuver can be repeated for different limits of the rudder and heading angle at each execution of the program if this is desired.
4. Calculation of spiral maneuver. This maneuver is executed as usual starting with a specified positive rudder deflection, stepwise reducing the rudder angle to a specified negative rudder deflection and vice versa. To obtain an accurate determination of a possible loop phenomenon, a smaller difference between consecutive rudder positions can be specified in the range around zero rudder deflection (see figure on data form, page 52).

Port or left rudder is considered a positive rudder deflection in the program. Similarly, starboard or right rudder corresponds to a negative deflection. The rudder deflections should be specified accordingly in the data forms.

The 35-deg turning circle, 20-20 deg zig-zag, and spiral maneuvers are referred to as the "Standard Maneuvers" which are used to evaluate performance qualities of a surface ship. The maneuvers, which have been specified on the example of the data form in Appendix A, actually correspond to those "Standard Maneuvers."

A graphic display of the computer results, that is, turning circle trajectory, zig-zag, and spiral maneuver can be obtained directly from the TMB computer by means of the on-line Charactron plotting equipment.

Such a plotting of the results can be specified on the data form as a part of the specification data.

Ship Data

The ship data have been divided into three groups: (1) Principle ship data, page 53, (2) EHP-data and open-water propeller characteristics, pages 54-55 , and (3) nondimensional coefficients, page 56.

The principle ship data include particulars such as ship length, beam, draft, displacement, propeller dimensions, wake coefficient, thrust deduction coefficient, etc. This group of data, furthermore, incorporates values for the rudder system, such as rudder rate and timelag discussed previously in the section "Definition of Rudder Deflection," page 16.

The ship effective horsepower data and open-water characteristics for the propeller (Data Group 2) together with data for approach speed, wake coefficient, thrust deduction coefficient, and information about the type of the ship propulsion plant (Data Group 1) are the basis for calculating the coefficients X_u, X_{uu}, and X_{uuu}, as discussed in the section "Calculation of Coefficients in X-Equation," page 19. The ship effective horsepower data should be given for a range of speed values covering the values to be encountered during the maneuvers. The roughness or extrapolation allowance used in the preparation of these data should correspond to the condition of the ship hull roughness for which the maneuvering predictions are desired. Similarly, the wake and thrust deduction coefficients should be actual ship values; for instance, those obtained from model tests and corrected for possible scale effects.

The calculation of the X_u, X_{uu}, and X_{uuu} coefficients can be based either on the assumption that propeller revolutions will be kept constant

during the maneuvers or on the assumption that propeller torque will vary proportionally to propeller revolutions in a certain power. In the first mentioned case, the input value named TYPE on the data form should be chosen as a value smaller than -5.0, whereas in other cases TYPE represent the power factor in the propeller torque equation:

$$Q_t/Q_{t_1} = (n_t/n_{t_1})^{TYPE} \tag{23}$$

The proper value of the power factor depends upon the type of power plant and should be estimated from information about the actual ship under consideration. If TYPE=0, Equation (23) would represent the case where torque remains constant during a maneuver since $Q_t = Q_{t_1}$. This would largely correspond to the conditions of a Diesel engine, which would develop a constant torque independent of speed and propeller revolutions so long as the engine setting is kept constant. If TYPE=-1.0, Equation (23) would change to $Q_t \cdot n_t = Q_{t_1} \cdot n_{t_1}$, which actually would correspond to a turbine capable of maintaining a constant power output (which, for instance, would be the case for a turbine with semi-automatic throttle control).

The nondimensional coefficients to be stated as the last group of the ship data (Data Group 3) are those coefficients obtained from captive model testing, previously discussed in the Chapter "Coefficients in Mathematical Model," page 17. Tables 1, 2, and 3, pages 25-27, show the relationship between the hydrodynamic derivatives in the mathematical model, Equation (10), and the corresponding identifiers used in the program, and on the data form. The tables also give the nondimensionalizing factors, to be used in the data preparation.

The data forms in Appendix A give, as an example, values of the various ship data corresponding to a cargo ship. Except for coefficients $Y_{\delta u}$ and $N_{\delta u}$, these data have been taken from the data and coefficients published in Reference 5 for the MARINER hull form. The coefficients $Y_{\delta u}$ and $N_{\delta u}$ are thought to be of some importance for the accuracy of the predictions, but they have been put equal to zero in the data forms as no model tests are available at present.

The data forms are, in general, thought to be self-explanatory. They contain the FORMAT specifications which necessarily must be known for the preparation of the punched cards.

OUTPUT FORM

The output from the computer program is presented in the form of a printed "prediction report" and, if desired, as graphs plotted by means of the Charactron Microfilm Recorder. An example of both types of output is given in Appendix B, which presents the results corresponding to the input data shown in the data forms, Appendix A. The following discussion of the output refers to the example in Appendix B.

Prediction Report

The first pages of the prediction report define precisely the input data on the basis of which the prediction has been carried out. On PAGE 1 it gives the principal ship data; on PAGE 2, the EHP-data and open-water propeller curves; and on PAGE 3, the nondimensional hydrodynamic coefficients; see pages 58-60.

PAGE 2 of the output shows the calculation of the coefficients X_u, X_{uu}, and X_{uuu}, which in this case has been carried out under the assumption

of a constant power output from the turbine (this means that propeller torque multiplied by propeller revolutions has been kept constant for the different values of speed). It is seen that this power assumption gives a slight variation of the propeller revolutions, varying from 68.6 rpm at the 15-knot approach speed to 55.5 at a speed of 7.0 knots.

To facilitate a straightforward evaluation of the inherent dynamic stability of the ship, the output includes on PAGE 3 values for the non-dimensional stability criterion and stability roots as well as the slope of the r-δ curve in $\sec^{-1}$. These quantities have been computed on the basis of the linear theory according to which the criteria for dynamic stability as mentioned in Equation (9) become:

$$C = Y_v(N_r - mx_G u_1) - N_v(Y_r - mu_1) > 0 \tag{9}$$

The stability roots, which all should be negative for a stable ship, are, in accordance with Reference 3, defined by

$$\left.\begin{matrix}\sigma_1 \\ \sigma_2\end{matrix}\right\} = \left\{\begin{matrix}\text{SIGMA 1} \\ \text{SIGMA 2}\end{matrix}\right\} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2 \cdot A}$$

$$\sigma_3 = \text{SIGMA 3} = X_u/(m - X_{\dot{u}}) \tag{24}$$

where:

$$A = (m - Y_{\dot{v}})(I_z - N_{\dot{r}}) - (mx_G - Y_{\dot{r}})(mx_G - N_{\dot{v}}),$$

$$B = -(m - Y_{\dot{v}})(N_r - mx_G u_1) - (I_z - N_{\dot{r}})Y_v + (mx_G - Y_{\dot{r}})N_v + (mx_G - N_{\dot{v}})(Y_r - mu_1), \text{ and}$$

C = stability criterion, Equation (9).

The slope of the r-δ curve, which represents the change in angular velocity r for a small rudder deflection δ, is expressed by

$$\frac{\partial r}{\partial \delta} = -\frac{(Y_v N_\delta - N_v Y_\delta)}{C} \cdot \frac{u_1}{LBP} \qquad \text{(in (deg/sec)/deg)} \tag{25}$$

The slope is negative for a stable ship, infinite for the marginally stable ship, and positive for the unstable ship as indicated in Figure 4.

The next pages of the prediction report give the results from the four different types of calculation which, as described previously, can be carried out by the program:

1. Calculation of turning circle parameters, PAGE 4
2. Calculation of turning circle for specified rudder angle, PAGE 5
3. Calculation of zig-zag maneuver, PAGE 7
4. Calculation of spiral maneuver, PAGE 9.

It should be noted that the speed values given in the results correspond to the velocity vector $\vec{U} = \sqrt{u^2 + v^2}$ and not to the forward component u of the velocity.

Charactron Microfilm Plotting of Maneuvers

The Charactron Plotting Equipment, which is available as an on-line output facility at TMB, permits the plotting and recording of results directly on microfilm, to be developed and enlarged subsequently. Pages 68-70, Appendix B, show examples of the three types of plots that can be obtained from the computer program in this way.

The plot of the turning circle trajectory, page 68, gives the path of the origin of the ship. The origin of the coordinate axis system corresponds to the point of rudder execute. The plotting is continued until a 540-deg turning circle has been completed.

The plot of the zig-zag maneuver, page 69, gives the well-known presentation of rudder angle and heading angle on a time basis. Rudder positions are indicated by an asterisk plotted every 10 sec. Similarly,

the heading angle is plotted with 10-sec time intervals, but in this case a straight line connecting subsequent points produces the "continuous" curve seen in the graph. In this connection, it should be noted that the program is based on a solution of the mathematical model using a time interval of 1 sec, as mentioned on page 16. However, the plotting of the maneuvers has been based on points with time intervals of 10 sec only in order to reduce the amount of data to be stored in the computer. The somewhat stepwise appearance of the heading angle curve is, for this reason, due to the method of plotting, and should not be taken as an expression for the accuracy of the computer solution.

The result from the spiral maneuver, page 70, is presented as a plot of rate of change of heading in degrees per second versus the different rudder positions. The results are plotted as discrete points only, and it might be necessary to consult the printed results in order to separate points obtained during the spiral maneuver for decreasing and increasing rudder angle, respectively. (The line connecting the points on the example has not been drawn by the recorder, but has been inserted afterward by hand to help in reading the points on the graph.)

RESULTS OF SAMPLE CALCULATIONS

The output example presented in Appendix B has been calculated on the basis of hydrodynamic coefficients for the MARINER form measured by planar motion mechanism tests and reported in Reference 5. The comparison between full-scale trials and computer predictions given in Reference 5 shows that the computer solution of the nonlinear mathematical model presents an accurate method for the prediction of the "Standard Maneuvers." No measure-

ments were available for the coefficients $Y_{\delta u}$ and $N_{\delta u}$, which represent the first-order change of rudder derivatives Y_δ and N_δ with speed. It is thought, however, that inclusion of values for these coefficients would have improved the accuracy further, particularly in the prediction of tight maneuvers where a considerable speed loss takes place.

To demonstrate the potential of the computer program and its ability to give detailed information about the maneuvers, different sample calculations have been worked out and are presented in the following sections.

INFLUENCE OF TYPE OF POWER PLANT UPON THE SPEED LOSS IN MANEUVERS

The type of power plant has a considerable effect upon the speed loss which takes place during a maneuver. To show this influence, predictions of the "Standard Maneuvers" have been calculated for three different cases assuming constant propeller revolutions, constant engine power (turbine ship), and constant torque (Diesel ship), respectively. All three sets of predictions have been carried out on the basis of the MARINER coefficients for an approach speed of 15 knots. Thus, the prediction for the turbine ship corresponds to the results of the example given in Appendix B.

Figures 5 through 8 present some of the results obtained from the three predictions. Figure 5 shows change of propeller revolutions as a function of forward velocity, Figure 6 gives velocity turn entry transient for the 35-deg port rudder turning circle, and Figure 7 gives, similarly, change in velocity predicted for the zig-zag maneuver. In Figure 8, the results from the spiral maneuver have been presented in the usual form as rate of change of heading versus rudder angle.

The figures clearly indicate that the speed loss is greatly influenced by the power assumption. For the Diesel ship, it takes considerably more time before steady conditions are obtained, because the speed loss is also considerably greater (Figures 6 and 7).

Free-running model tests, which often would be carried out for constant propeller revolutions, would apparently indicate a smaller speed loss and a shorter transition period than full-scale trials.

The trajectories of the predicted maneuvers have been found to be independent of the power assumption. This would not have been the case had coefficients for $Y_{\delta u}$ and $N_{\delta u}$ been included in the set of coefficients used for the predictions. Nevertheless, it indicates that trajectories, in general, would be independent of the speed loss encountered during a maneuver. This further indicates that it might be advantageous to compare and evaluate maneuvering performance on the basis of measurements, which are independent of the speed loss and consequently are independent of the power plant in the ship. Results from the spiral could be presented in a form suggested in Figure 9 as a plot of the reciprocal of the turning radius versus rudder deflection instead of in the usual graph shown in Figure 8, which is influenced by the power assumption. This representation would, in general, be independent of the power assumption, which might be difficult to obtain correctly from full-scale trials. Results from the three sets of predictions would in this way be plotted as a single curve independent of the speed loss.

Similarly, evaluation of the zig-zag maneuver on the basis of "period" and "reach" (see Figure 3) would be influenced (but only slightly) by the

power assumption. An evaluation based on factors independent of time would be preferable.

PREDICTION OF ZIG-ZAG MANEUVERS FOR DIFFERENT VALUES OF SHIP INERTIA.

The predictions presented in Appendix B have been computed on the basis of an approximate value for the ship moment of inertia I_z. The nondimensional value for the inertia has been taken as $I_z' = 39.2 \cdot 10^{-5}$, and the nondimensional coefficient as $(I_z' - N_{\dot{r}}') = \text{N RDOT} = 82.9 \cdot 10^{-5}$. Any inaccuracy in this value would in particular have an effect on the prediction of the zig-zag maneuver. To estimate this influence, supplementary calculations have been carried out, assuming the inertia to be 25 percent larger and smaller, respectively. The effect of this change is shown in Figure 10. The characteristic measures, overshoot, reach, and period as defined in Figure 3, are influenced, but nevertheless it is comforting to see that even a considerable error in the estimation of ship inertia would introduce only a small change in the maneuvering qualities of the ship.

This example at the same time indicates the flexibility of the prediction method. Model testing can be executed for any value of model inertia, because the appropriate ship value can be introduced at the time of data preparation for the computer program. This is in contrast to the free-running model technique, where model inertia should be properly scaled. Furthermore, strictly speaking, model results would correspond to only one value of ship inertia.

PREDICTION OF LOOP PHENOMENON IN SPIRAL MANEUVER

The application of the nonlinear mathematical model makes it possible to give realistic maneuvering predictions even for ships which are dynami-

cally unstable on a straight course. This is illustrated by Figure 11, which shows results from the spiral maneuver predicted for four different hull forms, two of which have been unstable while the others have been marginally stable and stable, respectively. The figure shows plots of the rate of change of heading versus rudder angle, and it is seen that the unstable ships exibit a zone in which there is a lack of preferential rate of change of heading with rudder angle. The "loop" phenomenon associated with an unstable hull form has thus been reconstructed exactly by the computer program.

Table 4 - Nondimensional Coefficients Governing the Criteria for Dynamic Stability for Stable, Marginally Stable, and Unstable Hull Forms

Nondim. Coeff.	Hull Form Stable MARINER	Hull Form Marginally Stable	Hull Form Unstable	Hull Form Unstable
$Y_v \cdot 10^5$	-1160.4	-1044.0	-928.0	-812.0
$N_v \cdot 10^5$	-263.5	-290.0	-316.0	-343.0
$Y_r \cdot 10^5$	298.0	268.0	238.0	209.0
$N_r \cdot 10^5$	-184.3	-166.3	-147.3	-129.3
$(Y_r - mu_1) \cdot 10^5$	-499.0	-529.0	-559.0	-588.0
$(N_r - mx_G u_1) \cdot 10^5$	-166.0	-148.0	-129.0	-111.0
$C \cdot 10^5$	0.61	0.01	-0.57	-1.12

The curve representing the stable ship corresponds to the results presented in previous examples predicted on the basis of the hydrodynamic coefficients for the MARINER form. The results for the marginally stable and unstable hull forms have been obtained on the basis of hydrodynamic coefficients derived from the MARINER values by changing the four coefficients

Y_v, N_v, Y_r, and N_r, which govern the criterion for dynamic stability given in Equation (9). Thus, in order that C becomes zero for the marginally stable and negative for the unstable, the derivatives have been changed 10, 20, and 30 percent as shown in Table 4.

SLOPED LOOP PHENOMENON IN SPIRAL MANEUVER

It is important in the execution of a full-scale spiral maneuver to wait a sufficient period of time until steady conditions have been reached before measuring rate of change of heading, speed, etc., and before ordering the next rudder deflection. For certain rudder positions, it might, however, take a considerable time before the motion becomes steady or it might be difficult to recognize that the ship actually is in a transition period. For this reason, measurements might be taken too hastily. As a result, the spiral maneuver can exibit a sloped loop phenomenon even for a ship that is in reality perfectly stable.

To illustrate the sloped loop phenomenon, predictions have been carried out for the (stable) MARINER form used in previous examples, executing the spiral maneuver with a limited time interval between consecutive rudder deflections. The spiral maneuver has been computed in two cases using time intervals of 60 and 120 sec, respectively. The results from these predictions are shown in Figure 12 together with the results from the spiral maneuver, where no time limit has been applied. It is seen that a double curve or sloped loop is obtained in the cases where premature measurements have been taken.

The possibility of a sloped loop phenomenon should be kept in mind, especially when evaluating the full-scale spiral maneuver results from a

ship which might be marginally stable. A sloped loop would, in such a case, easily be interpreted as the loop associated with a dynamically unstable ship.

CONCLUSIONS

The computer program permits the calculation of steering and maneuvering trials of surface ships giving predictions of the turning circle, zig-zag and spiral maneuvers. Predictions are presented in the form of a printed report and graphs plotted by the on-line Charactron Microfilm Recorder.

The program is based on the solution of a nonlinear mathematical model describing the motion of a ship in the horizontal plane. The mathematical model is developed from the equations of motion using a third-order Taylor expansion of forces and moments. The model has been reduced to a solvable form on the basis of the following assumptions:

1. Influence from rolling of the ship is negligible upon maneuvering predictions (page 6).
2. Forces and moments can be considered to be symmetrical except for side force from propeller (pages 10 and 11).
3. No second or higher order acceleration terms can be expected in the Taylor expansion of forces and moments. Similarly, cross-coupling between acceleration and velocity parameters is negligible (page 11).
4. Change of nondimensional coefficients Y_v', Y_r', N_v', N_r' with speed is negligible (page 23).

Input to the program can be prepared by means of data forms. The data consist of the hydrodynamic force and moment coefficients measured by

captive model test technique, ship EHP-data, open-water propeller characteristics, as well as data for the rudder system and type of power plant of the ship.

The combination of captive model testing and the computer prediction of maneuvers permits scaling laws to be taken into account in a proper fashion. The hydrodynamic coefficients can be obtained from captive model tests executed with the model propelled at the ship propulsion point. It is further emphasized that coefficients, if experience is available, can be corrected for Reynolds number effects. Coefficients, which are of principal importance for the determination of speed loss during maneuvers, are computed in the program from ship resistance values, eliminating the scale effect problem arising because of the difference between ship and model resistance.

The application of the nonlinear mathematical model makes it feasible to give accurate predictions for any type of maneuvers including tight maneuvers. Also the loop phenomenon associated with the spiral maneuver for a ship which is dynamically unstable on a straight course is readily obtained by the program

RECOMMENDATIONS

Most of the assumptions on which the computer program is based have been shown to hold true, e.g., in the experimental measurements reported in Reference 5. However, further model tests are recommended in order to confirm the assumptions.

Comparison between full-scale trials and computer predictions given in Reference 5 shows a promising agreement. Additional tests should be

carried out for the MARINER form to obtain coefficients $Y_{\delta u}$ and $N_{\delta u}$ to prove that an even better agreement can be obtained in the prediction of tight maneuvers in case these coefficients are included.

Measurements of hydrodynamic coefficients should be obtained for more hull forms, for which reliable full-scale trials are available so as to permit comparison with computer predictions and to obtain experience with respect to prediction accuracy.

Corrections of hydrodynamic coefficients for Reynolds number effect should be explored further, as present experience is insufficient to permit the introduction of reliable corrections.

ACKNOWLEDGMENTS

The author wishes to acknowledge Professor Martin A. Abkowitz, M.I.T., and Mr. M. S. Chislett, Hydro- and Aerodynamics Laboratory, for their contributions to the development of the present computer program.

The nonlinear mathematical model adopted in the program was originally presented by Professor Abkowitz in a series of lectures at the Technical University of Denmark. The computer solution was further initiated by Professor Abkowitz and developed by Mr. Chislett in cooperation with the author as a part of the controllability study carried out at the Hydro- and Aerodynamics Laboratory.

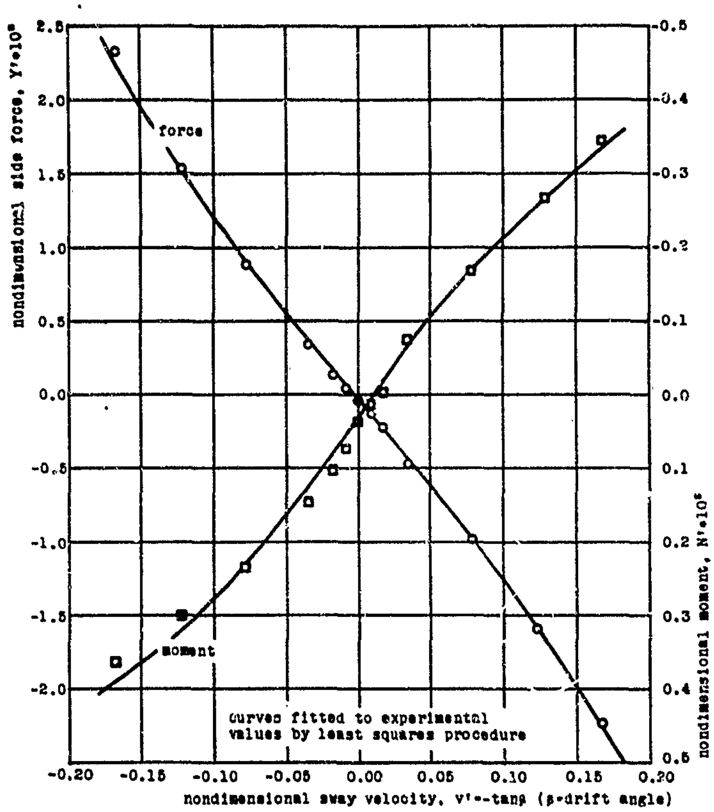


Figure 1 - Example of Measurements of Force and Moment as Function of Drift Angle

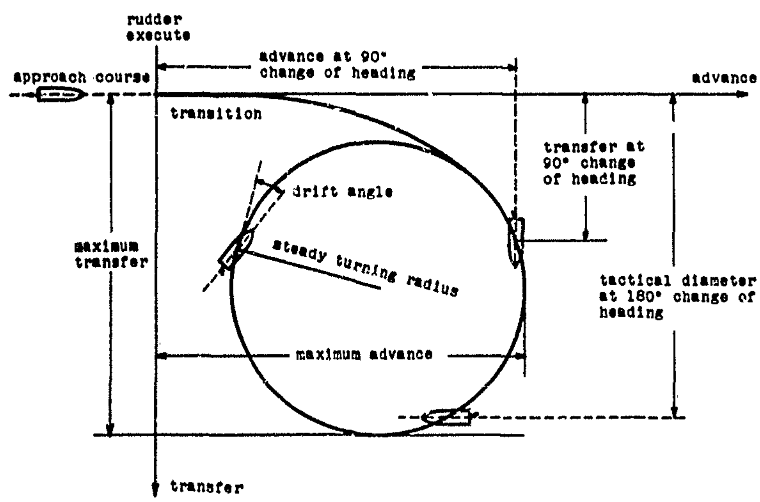


Figure 2 - Definition of Turning Circle Parameters

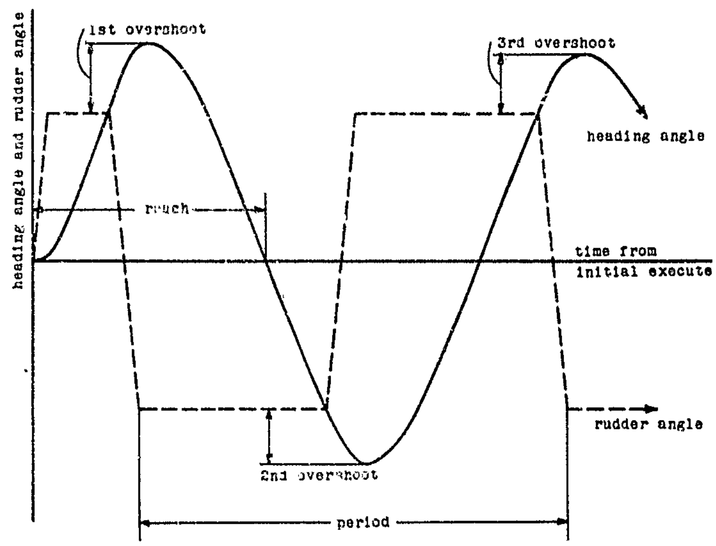


Figure 3 - Diagrammatic Definition of the Zig-Zag Maneuver

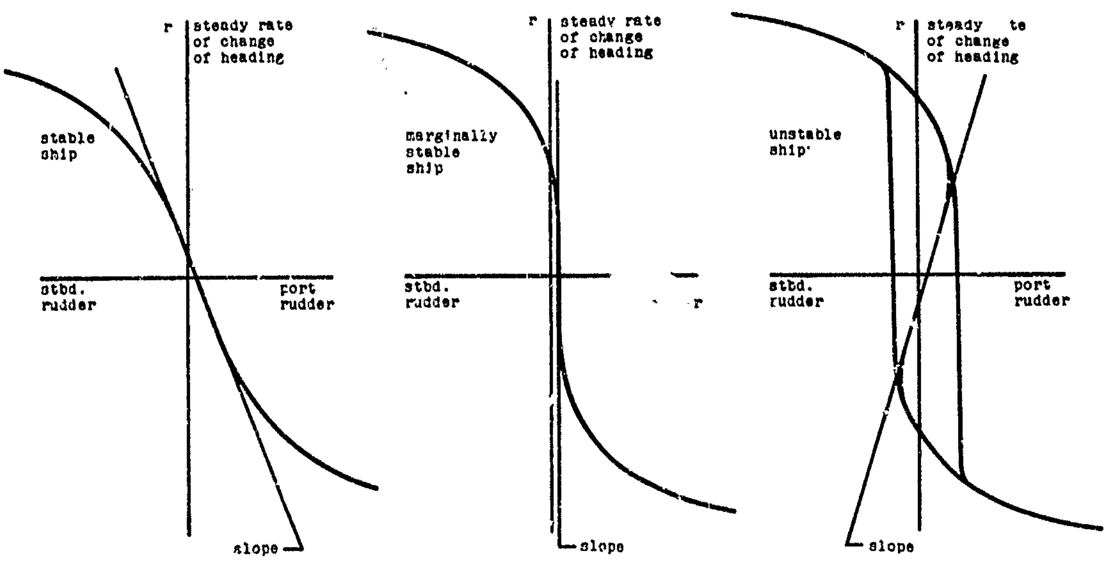
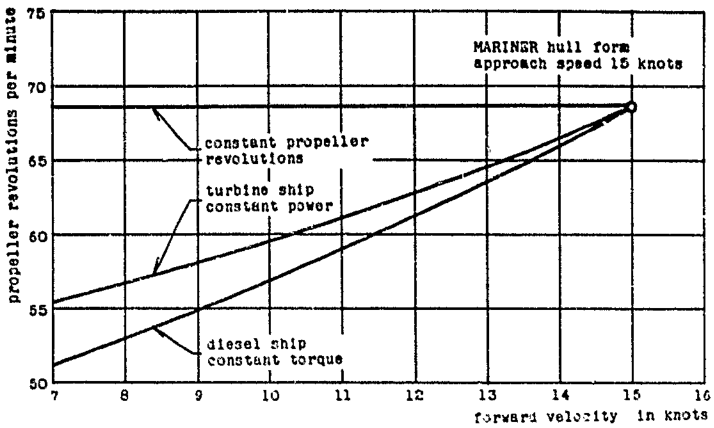


Figure 4 - Results from Spiral Maneuver Showing Slope of r-δ Curve for Stable, Marginally Stable, and Unstable Ships

Figure 5 - Change of Propeller Revolutions as Function of Speed-Loss in Maneuvers for Different Types of Power Plants



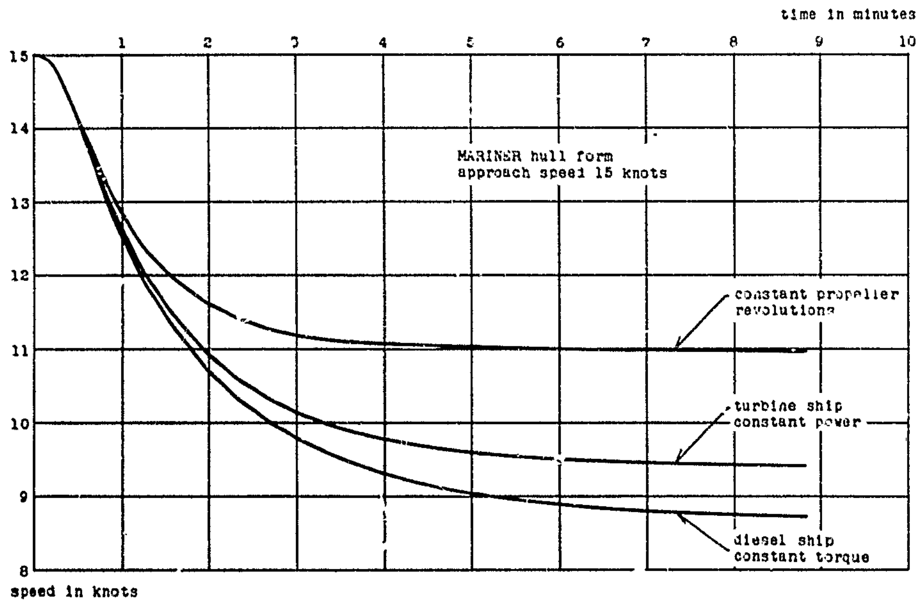


Figure 6 -
Velocity Turn Entry Transient for 35-Deg Rudder Computed for Different Types of Power Plants

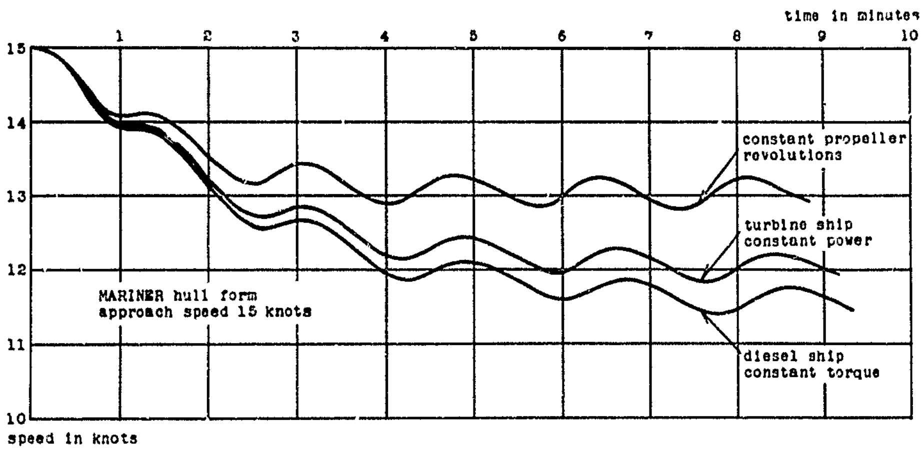


Figure 7 -
Time History of Velocity in Zig-Zag Maneuver Computed for Different Types of Power Plants

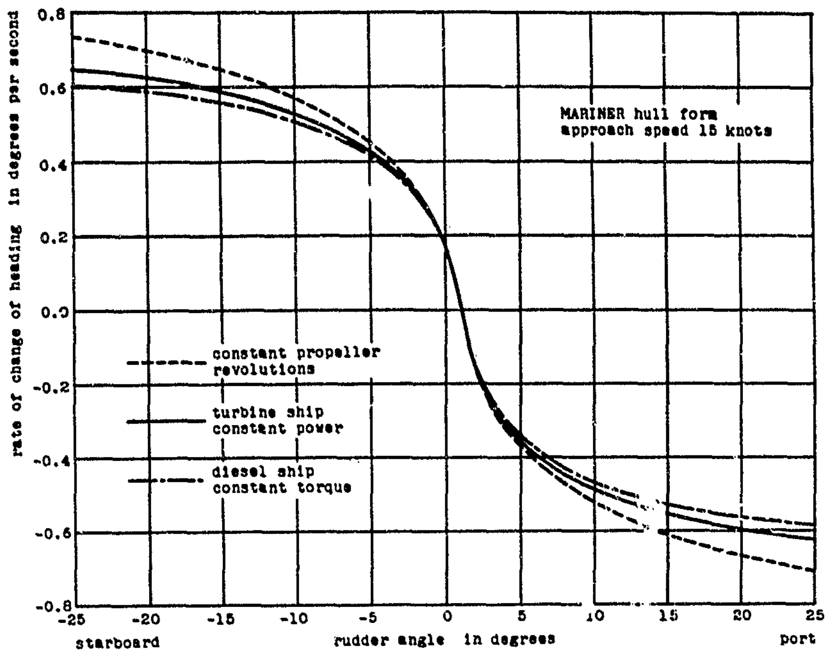


Figure 8 - Results from Spiral Maneuver as Influenced by the Assumption of Power Plant

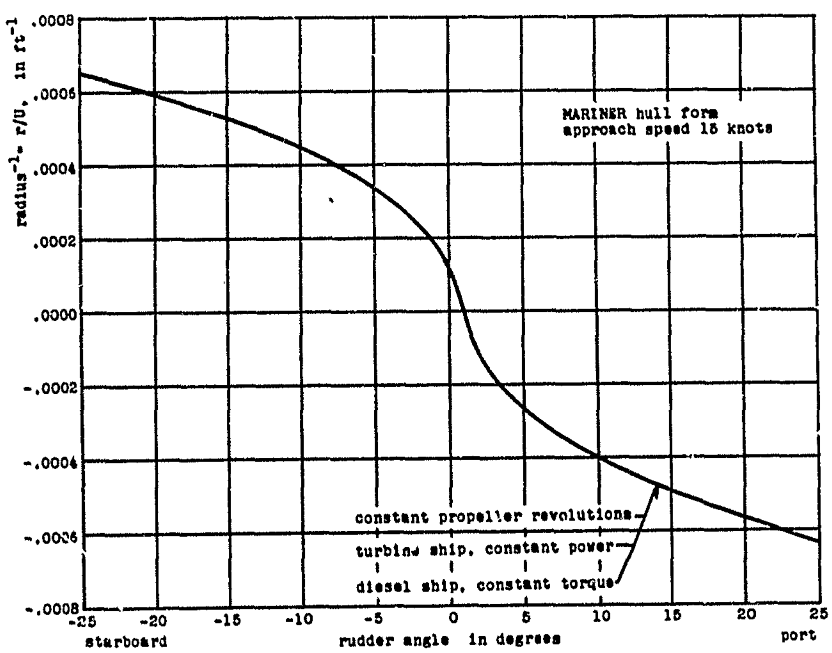


Figure 9 - Results from Spiral Maneuver Calculations Presented as Reciprocal of Turning Radius in Steady State versus Rudder Deflection

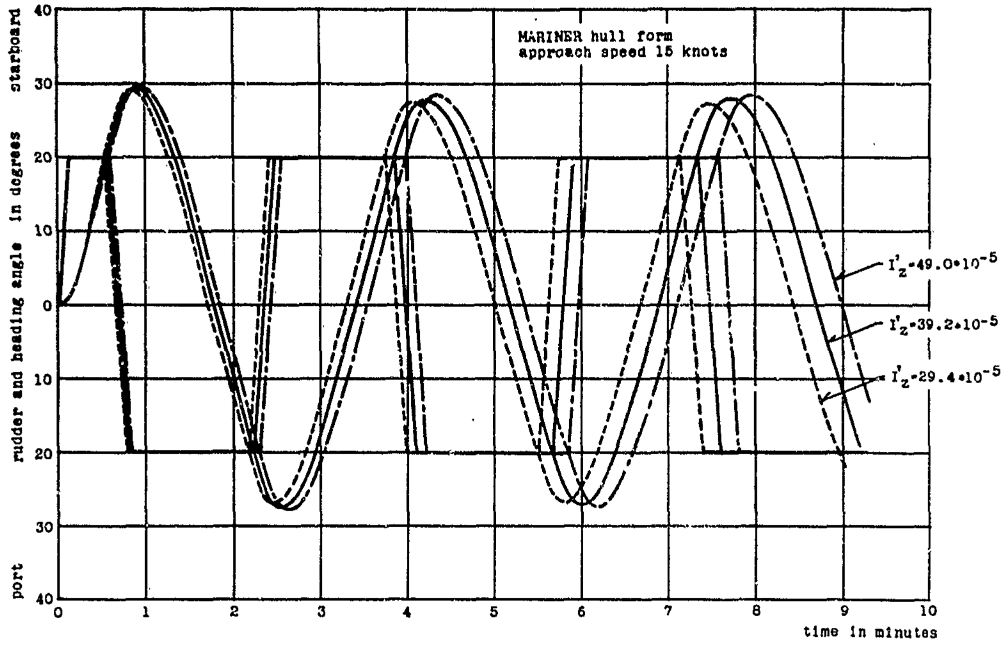


Figure 10 - Prediction of Zig-Zag Maneuvers for Three Different Values of Ship Moment of Inertia I_z

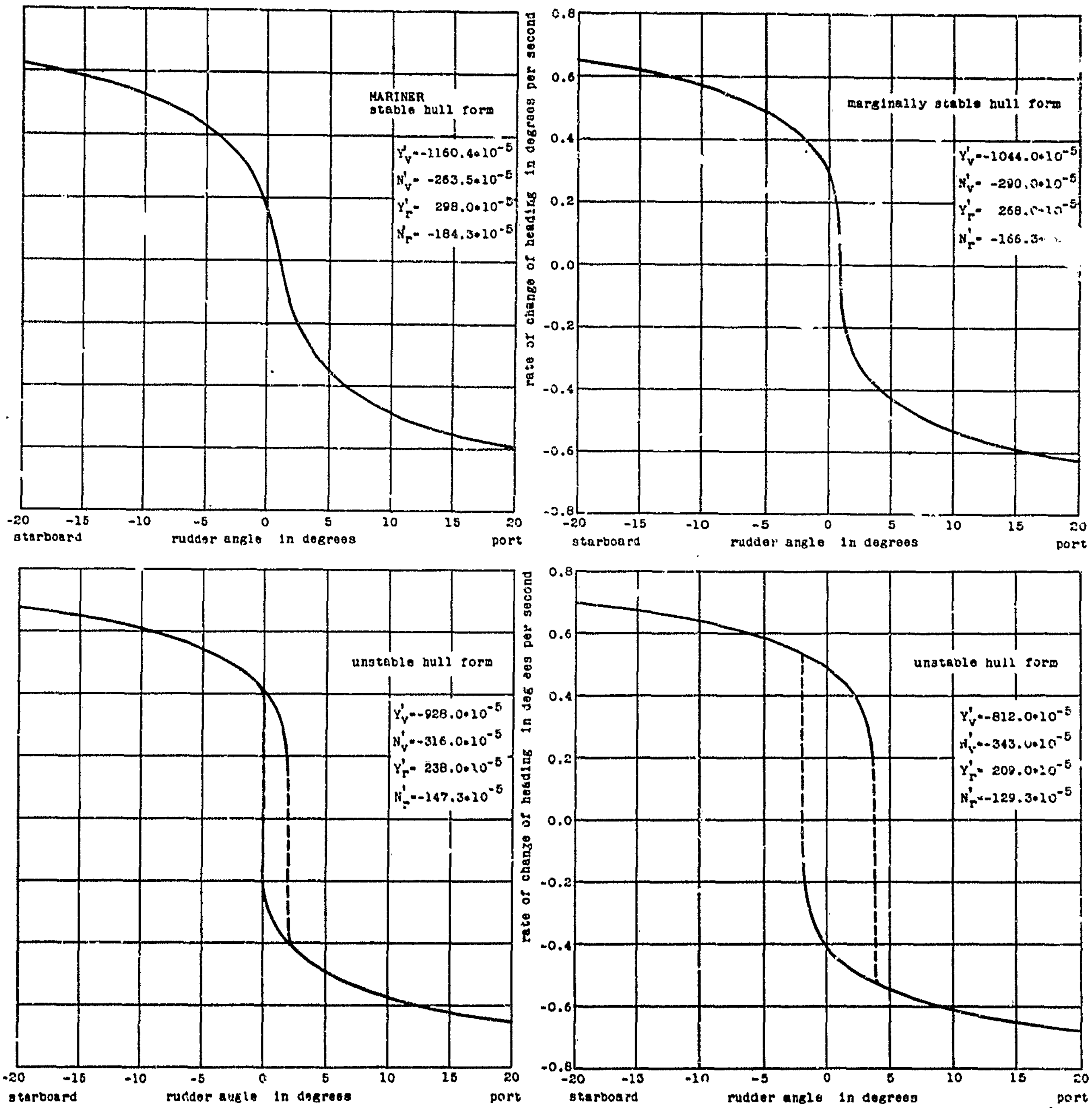


Figure 11 - Results from Prediction of Spiral Maneuver for Stable, Marginally Stable, and Unstable Hull Forms

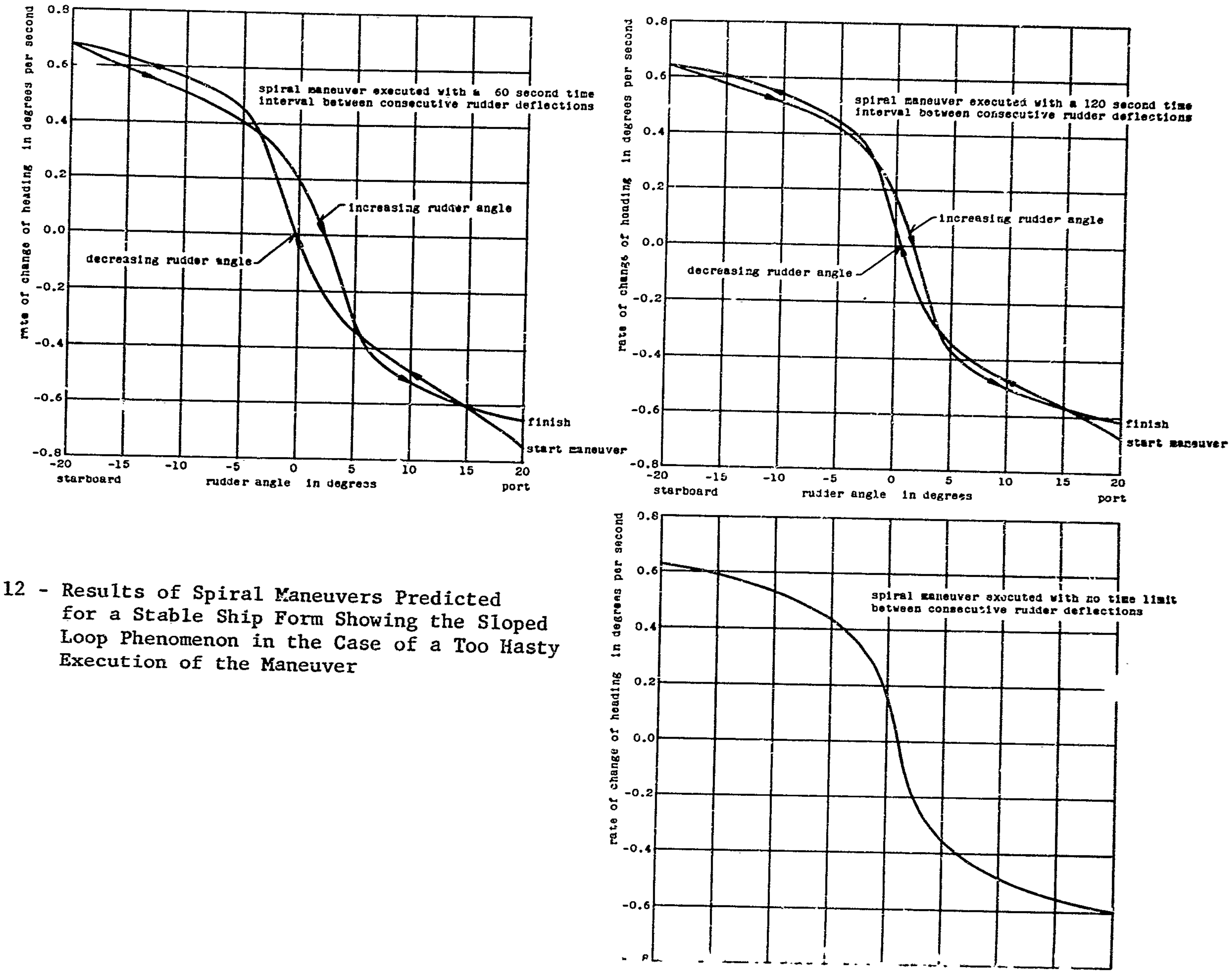


Figure 12 - Results of Spiral Maneuvers Predicted for a Stable Ship Form Showing the Sloped Loop Phenomenon in the Case of a Too Hasty Execution of the Maneuver

APPENDIX A

DATA FORMS FOR PREPARATION OF INPUT DATA

SPECIFICATION DATA - SPECIFICATION OF MANEUVERS TO BE PREDICTED

CARD SP 1 — FORMAT(9I8)

LTCP > 0, if turning circle parameters are to be computed.	LTCP =	1
LTC specify number of different rudder angles for which a turning circle trajectory should be predicted.	LTC =	1
LZZ specify number of zig-zag maneuvers to be computed.	LZZ =	1
LSM > 0, if spiral maneuver is to be computed.	LSM =	1
Turning circle trajectory, zig-zag, and spiral maneuver will be plotted if GRAPH > 0.	GRAPH=	1
LTEST > 0, if new set of input-data is to be read when this computation is executed.	LTEST=	0

Specification of Turning Circle Parameters: (If LTCP > 0 only)

CARD SP 2 — FORMAT(9F8.5)

DTC1 is smallest positive rudder angle in degrees for which parameters should be computed.	DTC1 =	5.0
DTCD is the difference between rudder angles for which parameters should be computed.	DTCD =	5.0
DTC2 is maximum rudder angle in degrees for which parameters should be computed.	DTC2 =	40.0

Specification for Calculation of Turning Circle Trajectory:
(Card to be punched if LTC 0 only)

CARD SP 3 — FORMAT(9F8.5)

Calculation of the turning circle trajectory will be carried out for LTC different rudder angles, which should be stated in the column to the right.

The rudder angles should be given in degrees, positive for port or left rudder, negative for starboard or right rudder.

DTC(1) =	35.0
DTC(2) =	
DTC(3) =	
DTC(4) =	

Specification for Zig-Zag Maneuver:
(Card to be punched if LZZ 0 only)

CARD SP 4 — FORMAT(9F8.5)

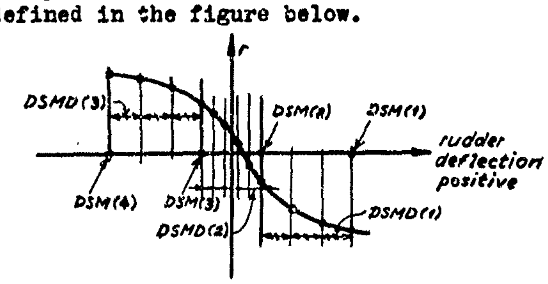
The zig-zag maneuver will be predicted for LZZ different rudder angles given as the DZZ-values in the column to the right.

DZZ(1) =	20.0
DZZ(2) =	
DZZ(3) =	
DZZ(4) =	

Specification of Spiral Maneuver:
(Card to be punched if LSM 0 only)

CARD SP 5 — FORMAT(9F8.5)

The execution of the spiral maneuver is defined by the seven parameters in the column to the right as defined in the figure below.



DSM(1) =	25.0
DSM(2) =	10.0
DSM(3) =	-10.0
DSM(4) =	-25.0
DSMD(1)=	5.0
DSMD(2)=	1.0
DSMD(3)=	5.0

SHIP DATA I - SPECIFICATION OF SHIP PARTICULARS, ETC.

Title of Computation: The title will be printed as a heading on all result sheets. Max. 72 characters. CARD SD 1 FORMAT(12A6)

HYA MARINER. PREDICTION ASSUMING CONSTANT POWER

Model Identification: CARD SD 2 FORMAT(9I8)

IMNO is the model number.		IMNO =	6295
IPNO is the propeller number.		IPNO =	6137

Principle Ship Data in condition tested : CARD SD 3 FORMAT(9F8.2)

Length between perpendiculars. Used for nondimensionalizing of coefficients	ft	ALFP =	528.01
Length on waterline	ft	ALWL* =	520.76
Beam moulded	ft	BMLD* =	76.02
Draft at forward perpendicular	ft	DFP* =	22.50
Draft at aft perpendicular	ft	DAP* =	25.70
L.C.G. measured from origin of axis system positive forward	ft	CG* =	-12.14
Radius of gyration measured with reference to origin of axis system	ft	RAD* =	117.92
Displacement	tons	DISP* =	16005.0
Number of propellers		PROP =	1.0

CARD SD 4 FORMAT(9F8.2)

Propeller diameter	ft	DIAM =	22.0
Pitch ratio at 0.7 diameter		PITCH* =	0.96
Projected propeller blade area ratio		AREA* =	0.52
Wake coeff. corresponding to condition of ship		WAKE =	0.160
Thrust deduction coeff. for ship		TDC =	0.136
Approach speed (define the initial condition)	knots	SPEED =	15.0
Rudder rate of deflection	deg/sec	RATE =	3.0
Timelag in rudder system	sec	TLAG =	0.0
Type of propulsion system TYPE= 0.0, if constant torque (DIESEL) TYPE=-1.0, if constant power (TURBINE) TYPE<-5.0, if constant propeller revolutions.		TYPE =	-1.0

* Data marked by asterisk are not used in the calculations. They are requested only in order to obtain a complete description of the ship in the condition tested.

SHIP DATA II - SHIP EFFECTIVE HORSEPOWER DATA and OPEN WATER PROPELLER CURVES

CARD SD 5 — FORMAT(9I8)

Number of points describing ship EHP-data: NEHP ≤ 18	NEHP =	9
Number of data points describing propeller curves: NPC ≤ 18	NPC =	11

Ship Effective Horsepower Data:

The ship EHP should be defined for a speed range covering the values to be encountered during the maneuvers.

Speed values in knots should be stated in the columns to the right in order of increasing values.

A set of NEHP speed values should be given (NEHP is defined above).
Only one punched card to be used if NEHP ≤ 9.

CARD SD 6.1 — FORMAT(9F8.2); CARD SD 6.2 — FORMAT(9F8.2)

CARD SD 6.1		CARD SD 6.2	
VS(1) =	7.0	VS(10) =	
VS(2) =	8.0	VS(11) =	
VS(3) =	9.0	VS(12) =	
VS(4) =	10.0	VS(13) =	
VS(5) =	11.0	VS(14) =	
VS(6) =	12.0	VS(15) =	
VS(7) =	13.0	VS(16) =	
VS(8) =	14.0	VS(17) =	
VS(9) =	15.0	VS(18) =	

Ship EHP data corresponding to the speed values above should be stated in the columns to the right.

The EHP values should be prepared using a roughness allowance corresponding to the ship condition for which the maneuvers are to be predicted.

CARD SD 7.1 — FORMAT(9F8.2); CARD SD 7.2 — FORMAT(9F8.2)

CARD SD 7.1		CARD SD 7.2	
EHP(1) =	286.0	EHP(10) =	
EHP(2) =	414.0	EHP(11) =	
EHP(3) =	582.0	EHP(12) =	
EHP(4) =	789.0	EHP(13) =	
EHP(5) =	1060.0	EHP(14) =	
EHP(6) =	1391.0	EHP(15) =	
EHP(7) =	1815.0	EHP(16) =	
EHP(8) =	2318.0	EHP(17) =	
EHP(9) =	2919.0	EHP(18) =	

SHIP DATA II - CONTINUED

Open Water Propeller Curves:

Propeller thrust coefficients, K_T, and torque coefficients, K_Q, should be defined for advance coefficients covering the range encountered during maneuvers.

Advance coefficients ADV= V/(n·D) should be stated in order of increasing values in the columns to the right.

A set of NPC data should be given. (NPC is defined on Page-3). If NPC > 9, two cards should be used.

CARD SD 8.1 FORMAT(9F8.5)		CARD SD 8.2 FORMAT(9F8.5)	
ADV(1)=	0.45	ADV(10)=	0.90
ADV(2)=	0.50	ADV(11)=	0.95
ADV(3)=	0.55	ADV(12)=	
ADV(4)=	0.60	ADV(13)=	
ADV(5)=	0.65	ADV(14)=	
ADV(6)=	0.70	ADV(15)=	
ADV(7)=	0.75	ADV(16)=	
ADV(8)=	0.80	ADV(17)=	
ADV(9)=	0.85	ADV(18)=	

Corresponding thrust coefficients

$K_T = T/(\rho n^2 D^4)$

should be given in the columns to the right.

CARD SD 9.1 FORMAT(9F8.5)		CARD SD 9.2 FORMAT(9F8.5)	
KT(1) =	0.291	KT(10) =	0.094
KT(2) =	0.270	KT(11) =	0.069
KT(3) =	0.250	KT(12) =	
KT(4) =	0.229	KT(13) =	
KT(5) =	0.209	KT(14) =	
KT(6) =	0.187	KT(15) =	
KT(7) =	0.165	KT(16) =	
KT(8) =	0.143	KT(17) =	
KT(9) =	0.118	KT(18) =	

Corresponding torque coefficients

$K_Q = Q/(\rho n^2 D^5)$

CARD SD 10.1 FORMAT(9F8.5)		CARD SD 10.2 FORMAT(9F8.5)	
KQ(1) =	0.0446	KQ(10) =	0.0191
KQ(2) =	0.0422	KQ(11) =	0.0156
KQ(3) =	0.0398	KQ(12) =	
KQ(4) =	0.0372	KQ(13) =	
KQ(5) =	0.0345	KQ(14) =	
KQ(6) =	0.0317	KQ(15) =	
KQ(7) =	0.0288	KQ(16) =	
KQ(8) =	0.0257	KQ(17) =	
KQ(9) =	0.0224	KQ(18) =	

SHIP DATA III - NONDIMENSIONAL COEFFICIENTS

X-equation coeff.×10^5 — CARD SD 11 — FORMAT(9F8.2)

$(m-X_{\dot{u}})$	X UDOT	840.0
$\frac{1}{2} X_{vv}$	X VV	-898.8
$(\frac{1}{2} X_{rr}+mx_G)$	X RR	18.0
$\frac{1}{2} X_{\delta\delta}$	X DD	-94.8
$(X_{vr}+m)$	X VR	798.0
$X_{v\delta}$	X VD	93.2
$X_{r\delta}$	X RD	0.0
XO	X O	0.0

Y-equation coeff.×10^5 — CARD SD 12 — FORMAT(9F8.2)

$(m-Y_{\dot{v}})$	Y VDOT	1546.0
$(mx_G-Y_{\dot{r}})$	Y RDOT	-8.6
Y_v	Y V	-1160.0
$\frac{1}{6} Y_{vvv}$	Y VVV	-8078.2
$\frac{1}{2} Y_{vrr}$	Y VRR	0.0
$\frac{1}{2} Y_{v\delta\delta}$	Y VDD	-3.8
(Y_r-mu)	Y R	-499.0
$\frac{1}{6} Y_{rrr}$	Y RRR	0.0
$\frac{1}{2} Y_{rvv}$	Y RVV	15356.0

CARD SD 13 — FORMAT(9F8.2)

$\frac{1}{2} Y_{r\delta\delta}$	Y RDD	0.0
Y_δ	Y D	277.9
$\frac{1}{6} Y_{\delta\delta\delta}$	Y DDD	-90.0
$\frac{1}{2} Y_{\delta vv}$	Y DVV	1189.6
$\frac{1}{2} Y_{\delta rr}$	Y DRR	0.0
$Y_{\delta u}$	Y DU	0.0
$Y_{vr\delta}$	Y VRD	0.0
YO	Y O	-3.6
YO_u	Y OU	0.0

N-equation coeff.×10^5 — CARD SD 14 — FORMAT(9F8.2)

$(mx_G-N_{\dot{v}})$	N VDOT	-22.7
$(I_z-N_{\dot{r}})$	N RDOT	82.9
N_v	N V	-263.5
$\frac{1}{6} N_{vvv}$	N VVV	1636.1
$\frac{1}{2} N_{vrr}$	N VRR	0.0
$\frac{1}{2} N_{v\delta\delta}$	N VDD	12.5
(N_r-mx_Gu)	N R	-166.0
$\frac{1}{6} N_{rrr}$	N RRR	0.0
$\frac{1}{2} N_{rvv}$	N RVV	-5483.0

CARD SD 15 — FORMAT(9F3.2)

$\frac{1}{2} N_{r\delta\delta}$	N RDD	0.0
N_δ	N D	-138.8
$\frac{1}{6} N_{\delta\delta\delta}$	N DDD	45.0
$\frac{1}{2} N_{\delta vv}$	N DVV	-489.0
$\frac{1}{2} N_{\delta rr}$	N DRR	0.0
$N_{\delta u}$	N DU	0.0
$N_{vr\delta}$	N VRD	0.0
NO	N O	2.8
NO_u	N OU	0.0

APPENDIX B

SAMPLE OF COMPUTER OUTPUT

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

PREDICTION OF STANDARD MANEUVERS

MODEL NUMBER 6295
PROP. NUMBER 6137

TABLE OF CONTENTS

PRINCIPLE SHIP DATA

LENGTH BETWEEN PERPENDICULARS . . . . =	528.01	FT
LENGTH ON WATER LINE . . . . =	520.76	FT
MOULDED BEAM . . . . =	76.02	FT
DRAFT AT F.P. . . . . =	22.50	FT
DRAFT AT A.P. . . . . =	25.70	FT
L.C.G. . . . . =	-12.14	FT
RADIUS OF GYRATION . . . . =	117.92	FT
DISPLACEMENT . . . . =	16005.	TONS
NUMBER OF PROPELLERS . . . . =	1.0	
PROPELLER DIAMETER . . . . =	22.00	FT
PITCH RATIO AT 0.7 R . . . . =	0.96	
PROJ. AREA / DISC AREA . . . . =	0.52	
REVOLUTIONS . . . . =	68.6	RPM
APPROACH SPEED . . . . =	15.00	KNOTS
RUDDER RATE . . . . =	3.00	DEG/SEC
TIME LAG OF RUDDER SYSTEM . . . . =	0.	SEC

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

CALCULATION OF THE NON-DIM. COEFFICIENTS XU, XUU, AND XUUU
ON THE BASIS OF SHIP EHP-DATA AND OPEN-WATER PROPELLER CURVES

X-FORCE = PROPELLER THRUST*(1-T) - RESISTANCE
= XU*DELU + XUU*DELU**2 + XUUU*DELU**3 (NON-DIM)
WHERE DELU = (U-U0)/U = NON-DIM.CHANGE IN FORWARD SPEED

X IS COMPUTED FOR

APPROACH SPEED	U0 =	15.00 KNOTS
WAKE COEFFICIENT	W =	0.160
THRUST DEDUCTION COEFFICIENT	T =	0.136

TURBINE SHIP - PROPELLER TORQUE VARY PROPORTIONAL TO
REVOLUTIONS IN -1.000 POWER DURING MANEUVRE

OPEN WATER PROPELLER CHARACTERISTICS (INPUT DATA)

ADVANCE COEFF. J	THRUST COEFF. KT	TORQUE COEFF. KQ
0.450	0.291	0.0446
0.500	0.270	0.0422
0.550	0.250	0.0398
0.600	0.229	0.0372
0.650	0.209	0.0345
0.700	0.187	0.0317
0.750	0.165	0.0288
0.800	0.143	0.0257
0.850	0.118	0.0224
0.900	0.094	0.0191
0.950	0.069	0.0156

SPEED	EHP-INPUT-DATA EHP	RESIST. *10-5	PROPELLER THRUST *10-5	TORQUE *10-5	REVS.	X *10-5	DELU	X *10+5	X*10+5 FAIRED
KNOTS		LB	LB	LB*FT	RPM	LB	0-DIM	0-DIM	0-DIM
15.0	2919.	0.6342	0.7340	3.0446	68.6				
7.0	286.	0.1332	1.1010	3.7643	55.5	0.8181	-1.143	211.23	211.23
8.0	414.	0.1687	1.0521	3.6777	56.8	0.7404	-0.875	146.36	146.32
9.0	582.	0.2107	1.0064	3.5919	58.1	0.6588	-0.667	102.90	103.02
10.0	789.	0.2571	0.9[illegible]23	3.5031	59.6	0.5743	-0.500	72.66	72.51
11.0	1060.	0.3140	0.9[illegible]70	3.4130	61.2	0.4782	-0.364	50.00	50.06
12.0	1391.	0.3778	0.8[illegible]22	3.3226	62.8	0.3758	-0.250	33.02	32.95
13.0	1815.	0.4550	0.8[illegible]74	3.2303	64.6	0.2598	-0.154	19.45	19.54
14.0	2318.	0.5396	0.7[illegible]16	3.1370	66.5	0.1357	-0.071	8.76	8.77
15.0	2919.	0.6342	0.7[illegible]41	3.0447	68.6	0.0000	0.	0.00	-0.03

COEFFICIENTS (NON-DIM)

XU = -120.0E-5
XUU = 45.0E-5
XUUU = -10.3E-5

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

C O E F F I C I E N T S (INPUT DATA)

THE FOLLOWING COEFFICIENTS OF THE EQUATIONS
OF MOTION ARE DESCRIBED IN DTMB REPORT NO.XXXX

X - E Q U A T I O N		Y - E Q U A T I O N		N - E Q U A T I O N	
VAR-IABLE	COEFF-ICIENT	VAR-IABLE	COEFF-ICIENT	VAR-IABLE	COEFF-ICIENT
X UDOT	840.0E-5	Y VDOT	1546.0E-5	N VDOT	-22.7E-5
		Y RDOT	-8.6E-5	N RDOT	82.9E-5
X U	-120.0E-5	Y V	-1160.4E-5	N V	-263.5E-5
X UU	45.0E-5	Y VVV	-8078.2E-5	N VVV	1636.1E-5
X UUU	-10.3E-5	Y VRR	-0. E-5	N VRR	-0. E-5
X VV	-898.8E-5	Y VDD	-3.8E-5	N VDD	12.5E-5
X RR	18.0E-5	Y R	-499.0E-5	N R	-166.0E-5
X DD	-94.8E-5	Y RRR	-0. E-5	N RRR	-0. E-5
X VR	798.0E-5	Y RVV	15356.0E-5	N RVV	-5483.0E-5
X VD	93.2E-5	Y RDD	-0. E-5	N RDD	-0. E-5
X RD	-0. E-5	Y D	277.9E-5	N D	-138.8E-5
		Y DDD	-90.0E-5	N DDD	45.0E-5
		Y DVV	1189.6E-5	N DVV	-489.0E-5
		Y DRR	-0. E-5	N DRR	-0. E-5
		Y DU	-0. E-5	N DU	-0. E-5
		Y VRD	-0. E-5	N VRD	-0. E-5
X 0	-0.0E-5	Y 0	-3.6E-5	N 0	2.8E-5
		Y 0U	-0. E-5	N 0U	-0. E-5

UNITS OF			0-DIM.WITH
	MASS	= LB*SEC**2/FT	RHO*LPP**3/2
	X AND Y FORCES	= LB	- - - RHO*LPP**2*U**2/2
	N MOMENT	= LB*FT	- - - RHO*LPP**3*U**2/2
	U AND V	= FT/SEC	- - - U
	R	= RADIANS/SEC	- - - U/LPP
	D	= RADIANS	
	UDOT AND VDOT	= FT/SEC/SEC	- - - U**2/LPP
	RDOT	= RADIANS/SEC/SEC	- - - U**2/LPP**2

S T A B I L I T Y R O O T S

SIGMA 1 = -0.1779E-00
SIGMA 2 = -0.2686E 01
SIGMA 3 = -0.1429E-00

STABILITY CRITERION = 0.6114E-05
SLOPE OF R-D CURVE = -0.1837E-00 (DEG/SEC)/DEG

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

T U R N I N G   C I R C L E   P A R A M E T E R S

RUD ANGLE DEG	ADVANCE (90 DEG) FT	TRANS-FER (90 DEG) FT	MAX ADVANCE FT	TACT DIAM FT	TIME FOR HDG CHANGE (90) SEC	TIME FOR HDG CHANGE (180) SEC	MAX TRANS-FER FT	STEADY TURN RAD FT	STEADY DRIFT ANGLE DEG	FINAL SPEED KNOTS
5.0	4859	-3637	4866	7615	278	530	-7623	3771.	-3.9	13.77
-5.0	3830	2846	3838	6043	220	426	6051	3001.	4.6	13.28
10.0	3175	-2321	3185	5033	184	364	-5042	2508.	-5.6	12.59
-10.0	2838	2072	2847	4509	165	329	4519	2249.	6.0	12.28
15.0	2574	-1852	2585	4091	151	306	-4102	2044.	-6.6	11.72
-15.0	2389	1707	2401	3796	140	285	3808	1898.	6.9	11.50
20.0	2249	-1582	2262	3567	133	275	-3580	1785.	-7.4	11.02
-20.0	2129	1496	2141	3367	126	261	3379	1685.	7.6	10.85
25.0	2049	-1428	2061	3228	123	257	-3241	1617.	-8.0	10.41
-25.0	1959	1350	1972	3076	117	246	3089	1541.	8.2	10.28
30.0	1914	-1309	1927	2990	116	246	-3003	1498.	-8.5	9.89
-30.0	1842	1246	1856	2866	111	236	2881	1437.	8.6	9.72
35.0	1818	-1214	1833	2817	111	239	-2832	1412.	-8.8	9.42
-35.0	1760	1167	1775	2714	107	231	2727	1360.	9.0	9.33
40.0	1751	-1147	1768	2691	108	236	-2706	1349.	-9.2	9.01
-40.0	1703	1118	1717	2598	105	228	2613	1302.	9.3	8.93

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

T U R N I N G   C I R C L E   F O R 35.0 D E G . R U D D E R

TIME AFTER EXECUTE SEC	RUDDER ANGLE DEG	ADVANCE FT	TRANS-FER FT	SPEED KNOTS	HEADING ANGLE DEG	ANGULAR VELOCITY DEG/SEC	DRIFT ANGLE DEG
0.	1.2	0.	0.	15.00	0.	0.	0.
10.0	31.2	252.7	-7.1	14.91	-2.0	-0.462	-1.6
20.0	35.0	501.2	-10.2	14.59	-9.8	-0.972	-5.2
30.0	35.0	740.4	-47.6	14.13	-20.3	-1.066	-7.6
40.0	35.0	962.6	-118.7	13.60	-30.6	-0.994	-8.7
50.0	35.0	1162.6	-220.5	13.09	-40.2	-0.923	-9.0
60.0	35.0	1337.8	-347.7	12.64	-49.1	-0.875	-9.1
70.0	35.0	1486.7	-494.9	12.25	-57.7	-0.842	-9.2
80.0	35.0	1608.9	-657.3	11.90	-65.9	-0.816	-9.2
90.0	35.0	1704.2	-830.8	11.61	-74.0	-0.795	-9.1
100.0	35.0	1773.0	-1011.5	11.35	-81.8	-0.777	-9.1
110.0	35.0	1815.8	-1196.0	11.13	-89.5	-0.761	-9.1
120.0	35.0	1833.3	-1380.9	10.93	-97.1	-0.748	-9.1
130.0	35.0	1826.7	-1563.5	10.76	-104.5	-0.736	-9.1
140.0	35.0	1797.2	-1741.1	10.60	-111.8	-0.726	-9.0
150.0	35.0	1746.2	-1911.2	10.47	-119.0	-0.717	-9.0
160.0	35.0	1675.1	-2071.6	10.35	-126.1	-0.709	-9.0
170.0	35.0	1585.8	-2220.5	10.25	-133.1	-0.701	-9.0
180.0	35.0	1479.9	-2356.0	10.16	-140.1	-0.695	-9.0
190.0	35.0	1359.4	-2476.7	10.07	-147.0	-0.690	-9.0
200.0	35.0	1226.3	-2581.2	10.00	-153.9	-0.685	-9.0
210.0	35.0	1082.6	-2668.5	9.94	-160.7	-0.680	-8.9
220.0	35.0	930.6	-2737.7	9.88	-167.5	-0.676	-8.9
230.0	35.0	772.3	-2788.2	9.83	-174.3	-0.673	-8.9
240.0	35.0	610.0	-2819.7	9.78	-181.0	-0.670	-8.9
250.0	35.0	445.8	-2832.0	9.74	-187.6	-0.667	-8.9
260.0	35.0	281.9	-2825.1	9.71	-194.3	-0.665	-8.9
270.0	35.0	120.5	-2799.4	9.68	-200.9	-0.662	-8.9
280.0	35.0	-36.4	-2755.3	9.65	-207.6	-0.661	-8.9
290.0	35.0	-186.8	-2693.7	9.62	-214.1	-0.659	-8.9
300.0	35.0	-328.7	-2615.4	9.60	-220.7	-0.657	-8.9
310.0	35.0	-460.5	-2521.6	9.58	-227.3	-0.656	-8.9
320.0	35.0	-580.4	-2413.5	9.56	-233.8	-0.655	-8.9
330.0	35.0	-687.0	-2292.7	9.55	-240.4	-0.654	-8.9
340.0	35.0	-779.1	-2160.7	9.53	-246.9	-0.653	-8.9

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

T U R N I N G   C I R C L E   F O R 35.0 D E G . R U D D E R
(CONTINUED)

TIME AFTER EXECUTE SEC	RUDDER ANGLE DEG	ADVANCE FT	TRANS-FER FT	SPEED KNOTS	HEADING ANGLE DEG	ANGULAR VELOCITY DEG/SEC	DRIFT ANGLE DEG
350.0	35.0	-855.4	-2019.3	9.52	-253.4	-0.652	-8.9
360.0	35.0	-915.1	-1870.3	9.51	-260.0	-0.651	-8.9
370.0	35.0	-957.5	-1715.7	9.50	-266.5	-0.650	-8.9
380.0	35.0	982.0	-1557.5	9.49	-273.0	-0.650	-8.9
390.0	35.0	-988.5	-1397.6	9.48	-279.5	-0.649	-8.9
400.0	35.0	-976.9	-1238.2	9.47	-285.9	-0.649	-8.9
410.0	35.0	-947.3	-1081.2	9.47	-292.4	-0.648	-8.9
420.0	35.0	-900.3	-928.6	9.46	-298.9	-0.648	-8.9
430.0	35.0	-836.4	-782.4	9.46	-305.4	-0.648	-8.9
440.0	35.0	-756.4	-644.5	9.45	-311.9	-0.647	-8.9
450.0	35.0	-661.4	-516.4	9.45	-318.3	-0.647	-8.9
460.0	35.0	-552.6	-400.0	9.44	-324.8	-0.647	-8.9
470.0	35.0	-431.5	-296.5	9.44	-331.3	-0.647	-8.9
480.0	35.0	-299.5	-207.4	9.44	-337.7	-0.646	-8.9
490.0	35.0	-158.4	-133.8	9.44	-344.2	-0.646	-8.9
500.0	35.0	-9.9	-76.5	9.43	-350.7	-0.646	-8.9
510.0	35.0	144.1	-36.3	9.43	-357.1	-0.646	-8.9
520.0	35.0	301.5	-13.7	9.43	-363.6	-0.646	-8.9
530.0	35.0	460.5	-8.9	9.43	-370.0	-0.646	-8.8
540.0	35.0	619.0	-23.0	9.43	-376.5	-0.646	-8.8
550.0	35.0	775.0	-52.9	9.43	-382.9	-0.645	-8.8
560.0	35.0	926.5	-101.1	9.42	-389.4	-0.645	-8.8
570.0	35.0	1071.6	-166.0	9.42	-395.9	-0.645	-8.8
580.0	35.0	1208.5	-246.8	9.42	-402.3	-0.645	-8.8
590.0	35.0	1335.4	-342.5	9.42	-408.8	-0.645	-8.8
600.0	35.0	1450.8	-451.8	9.42	-415.2	-0.645	-8.8
610.0	35.0	1553.1	-573.3	9.42	-421.7	-0.645	-8.8
620.0	35.0	1641.1	-705.6	9.42	-428.1	-0.645	-8.8
630.0	35.0	1713.7	-847.0	9.42	-434.6	-0.645	-8.8
640.0	35.0	1770.0	-995.6	9.42	-441.0	-0.645	-8.8
650.0	35.0	1809.2	-1149.5	9.42	-447.5	-0.645	-8.8

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

20.0 DEG. - 20.0 DEG. ZIG-ZAG MANEUVER

TIME AFTER EXECUTE SEC	RUDDER ANGLE DEG	ADVANCE FT	TRANS-FER FT	SPEED KNOTS	HEADING ANGLE DEG	ANGULAR VELOCITY DEG/SEC	DRIFT ANGLE DEG
0.	1.2	0.	0.	15.00	0.	0.	0.
10.0	-20.0	252.8	0.3	14.95	1.9	0.418	1.5
20.0	-20.0	503.8	10.0	14.82	8.1	0.743	4.0
30.0	-20.0	749.9	42.0	14.60	16.3	0.863	6.0
40.0	-5.0	985.7	103.0	14.32	24.7	0.738	6.7
50.0	20.0	1207.9	191.7	14.08	29.1	0.172	4.8
60.0	20.0	1420.7	294.7	13.97	28.7	-0.185	2.1
70.0	20.0	1631.5	399.7	13.95	25.4	-0.430	-0.6
80.0	20.0	1845.3	497.7	13.92	20.0	-0.626	-3.1
90.0	20.0	2064.5	579.8	13.83	13.1	-0.739	-5.1
100.0	20.0	2288.6	638.8	13.66	5.5	-0.767	-6.3
110.0	20.0	2514.8	670.7	13.44	-2.2	-0.754	-7.0
120.0	20.0	2739.5	674.4	13.22	-9.6	-0.733	-7.3
130.0	20.0	2959.3	650.8	13.01	-16.8	-0.715	-7.5
140.0	5.0	3171.3	601.0	12.83	-23.6	-0.600	-7.2
150.0	-20.0	3373.9	528.0	12.72	-27.2	-0.129	-5.1
160.0	-20.0	3570.6	442.5	12.71	-26.6	0.192	-2.3
170.0	-20.0	3766.9	354.5	12.78	-23.3	0.423	0.4
180.0	-20.0	3966.9	272.2	12.83	-18.0	0.615	2.9
190.0	-20.0	4172.3	203.5	12.83	-11.1	0.732	5.0
200.0	-20.0	4382.7	155.6	12.74	-3.6	0.765	6.4
210.0	-20.0	4595.2	132.3	12.61	4.0	0.755	7.1
220.0	-20.0	4806.5	135.2	12.46	11.5	0.735	7.5
230.0	-20.0	5013.3	163.8	12.31	18.7	0.717	7.6
240.0	4.0	5212.8	217.1	12.20	25.1	0.507	7.0
250.0	20.0	5404.1	291.0	12.14	27.7	0.080	4.7
260.0	20.0	5591.2	375.4	12.19	27.1	-0.161	2.2
270.0	20.0	5778.5	462.4	12.28	24.5	-0.348	-0.2
280.0	20.0	5969.3	545.9	12.38	20.1	-0.512	-2.4
290.0	20.0	6165.4	619.2	12.42	14.3	-0.628	-4.4
300.0	20.0	6367.0	676.3	12.41	7.6	-0.682	-5.8
310.0	20.0	6572.6	712.9	12.34	0.7	-0.691	-6.6
320.0	20.0	6779.5	726.8	12.25	-6.1	-0.682	-7.1
330.0	20.0	6985.0	717.2	12.15	-12.9	-0.670	-7.3
340.0	20.0	7186.3	684.7	12.05	-19.5	-0.660	-7.4

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

20.0 D E G . - 20.0 D E G . Z I G - Z A G M A N E U V E R
(CONTINUED)

TIME AFTER EXECUTE SEC	RUDDER ANGLE DEG	ADVANCE FT	TRANS-FER FT	SPEED KNOTS	HEADING ANGLE DEG	ANGULAR VELOCITY DEG/SEC	DRIFT ANGLE DEG
350.0	-7.0	7381.2	629.7	11.98	-25.2	-0.418	-6.6
360.0	-20.0	7569.5	556.7	11.96	-26.9	-0.000	-4.1
370.0	-20.0	7755.1	475.6	12.04	-25.5	0.247	-1.5
380.0	-20.0	7942.4	394.0	12.16	-21.9	0.448	1.0
390.0	-20.0	8134.2	318.8	12.24	-16.5	0.612	3.4
400.0	-20.0	8331.8	257.3	12.27	-9.8	0.707	5.2
410.0	-20.0	8534.2	215.2	12.23	-2.5	0.733	6.5
420.0	-20.0	8738.8	196.1	12.14	4.8	0.725	7.1
430.0	-20.0	8942.6	201.1	12.04	12.0	0.708	7.5
440.0	-20.0	9142.5	230.2	11.93	19.0	0.695	7.6
450.0	4.0	9336.0	282.6	11.85	25.2	0.497	7.0
460.0	20.0	9522.1	354.6	11.82	27.8	0.086	4.7
470.0	20.0	9704.4	437.0	11.89	27.3	-0.147	2.3
480.0	20.0	9887.2	522.5	12.01	24.8	-0.328	-0.0
490.0	20.0	10073.4	605.0	12.12	20.6	-0.487	-2.2
500.0	20.0	10264.9	678.6	12.19	15.1	-0.606	-4.2
510.0	20.0	10462.2	737.3	12.20	8.6	-0.666	-5.6
520.0	20.0	10663.9	776.7	12.16	1.9	-0.680	-6.5
530.0	20.0	10867.6	794.3	12.09	-4.9	-0.673	-7.0
540.0	20.0	11070.6	789.2	12.00	-11.6	-0.662	-7.2
550.0	20.0	11270.4	761.7	11.92	-18.1	-0.653	-7.4

HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

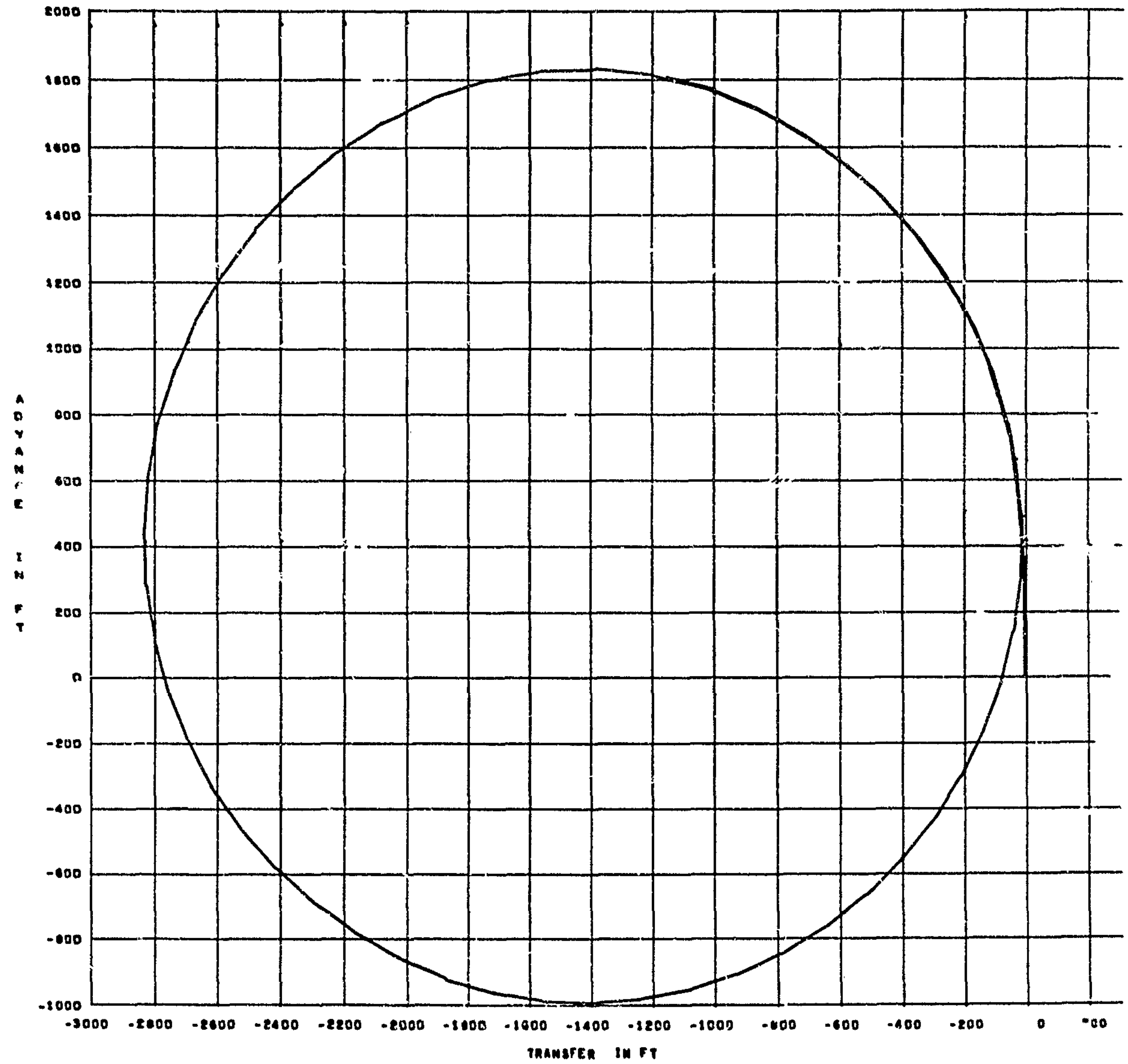
S P I R A L   M A N E U V E R

RUDDER ANGLE DEG	STEADY RATE OF CHANGE OF HEADING DEG/SEC	TIME TO REACH STEADY STATE SEC	SPEED IN STEADY STATE KNOTS	DRIFT ANGLE IN STEADY STATE DEG	TURNING RADIUS IN STEADY STATE FT
25.0	-0.623	605.0	10.41	-8.0	1616.8
20.0	-0.596	437.0	11.00	-7.4	1785.6
15.0	-0.553	482.0	11.70	-6.6	2044.6
10.0	-0.485	537.0	12.57	-5.6	2508.5
9.0	-0.465	372.0	12.77	-5.3	2653.6
8.0	-0.444	385.0	12.99	-5.0	2831.3
7.0	-0.418	400.0	13.22	-4.7	3055.9
6.0	-0.388	418.0	13.47	-4.3	3353.1
5.0	-0.352	440.0	13.74	-3.9	3773.0
4.0	-0.306	467.0	14.04	-3.3	4431.9
3.0	-0.245	504.0	14.38	-2.6	5684.3
2.0	-0.151	555.0	14.75	-1.6	9423.4
1.0	0.004	587.0	14.99	-0.0	361035.4
-0.	0.161	568.0	14.78	1.6	8896.1
-1.0	0.254	529.0	14.42	2.6	5494.5
-2.0	0.316	484.0	14.09	3.3	4318.0
-3.0	0.361	452.0	13.79	3.8	3690.5
-4.0	0.398	428.0	13.53	4.3	3287.5
-5.0	0.428	408.0	13.28	4.6	3000.7
-6.0	0.454	391.0	13.06	5.0	2783.2
-7.0	0.476	377.0	12.85	5.3	2610.6
-8.0	0.495	364.0	12.65	5.5	2469.2
-9.0	0.513	353.0	12.46	5.8	2350.6
-10.0	0.528	343.0	12.28	6.0	2249.2
-15.0	0.586	480.0	11.50	6.9	1898.3
-20.0	0.622	439.0	10.85	7.6	1685.4
-25.0	0.645	405.0	10.28	8.2	1540.8
-20.0	0.621	425.0	10.83	7.6	1685.5
-15.0	0.585	466.0	11.48	6.9	1898.5
-10.0	0.527	514.0	12.26	6.0	2249.6
-9.0	0.512	348.0	12.44	5.8	2351.0
-8.0	0.494	359.0	12.62	5.5	2469.7
-7.0	0.475	371.0	12.82	5.3	2611.
-6.0	0.453	384.0	13.03	5.0	2783.8
-5.0	0.427	399.0	13.26	4.6	3001.6

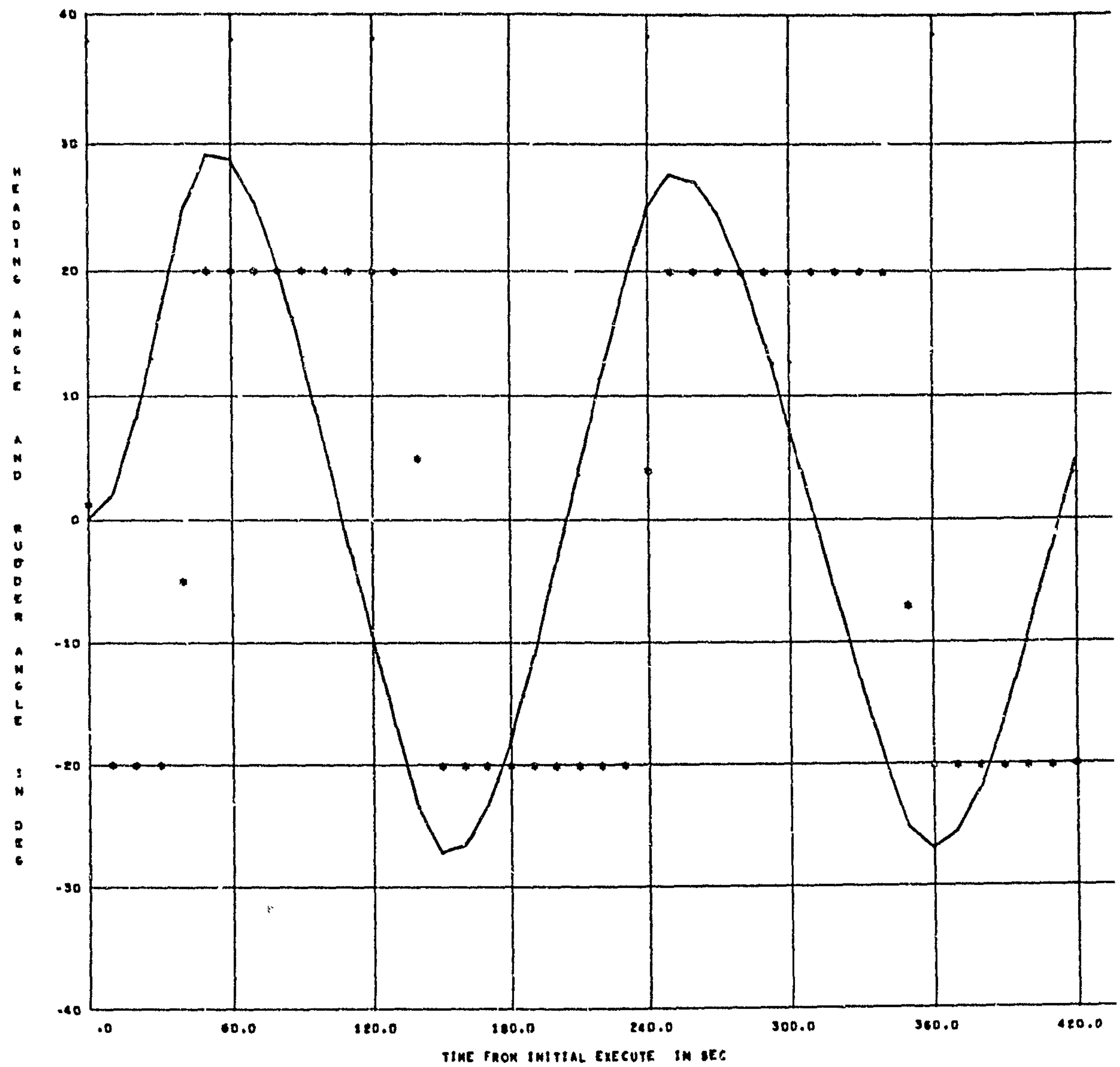
HY-A MARINER. PREDICTION ASSUMING CONSTANT POWER.

S P I R A L   M A N E U V E R   (CONTINUED)

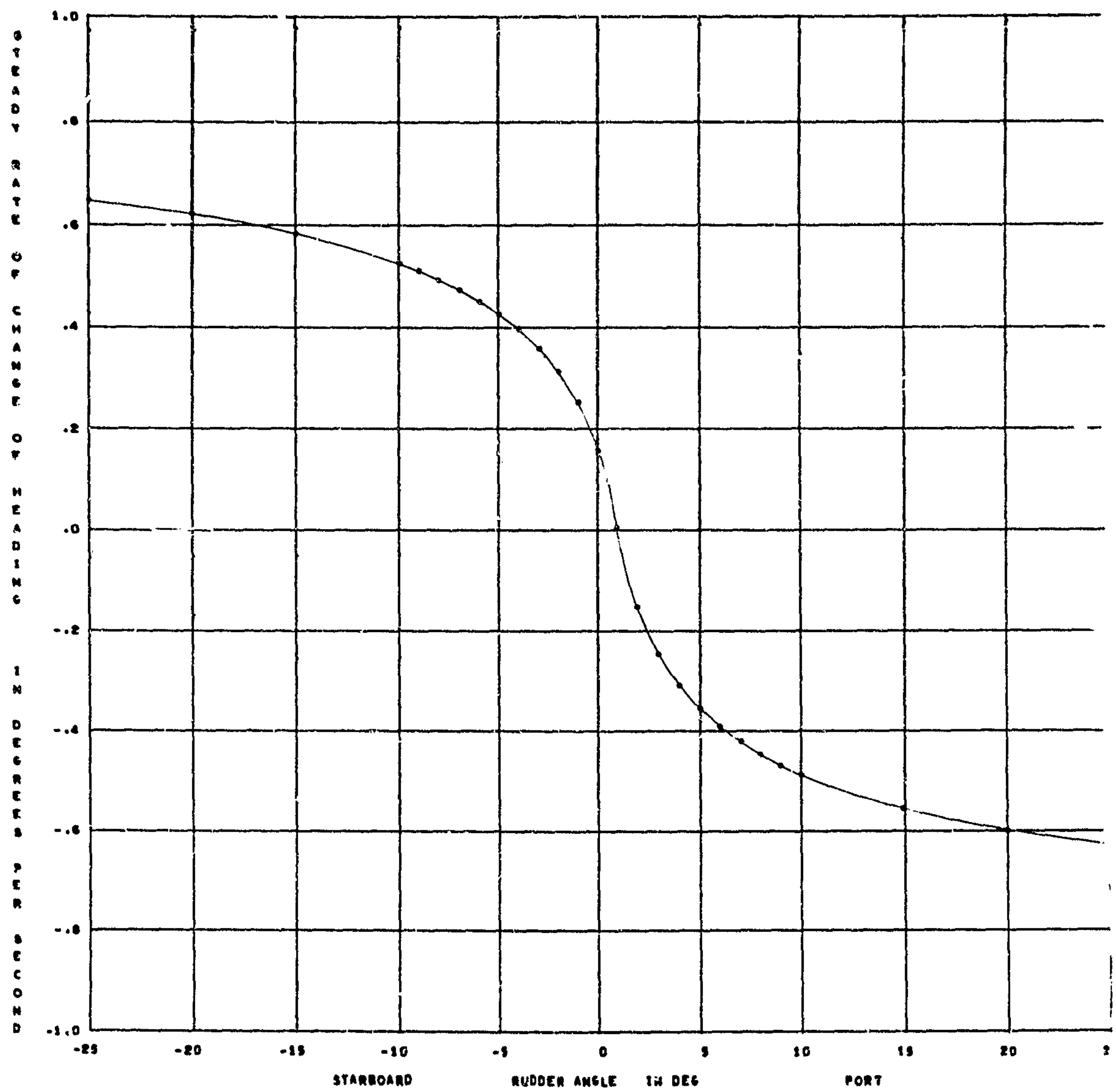
RUDDER ANGLE DEG	STEADY RATE OF CHANGE OF HEADING DEG/SEC	TIME TO REACH STEADY STATE SEC	SPEED IN STEADY STATE KNOTS	DRIFT ANGLE IN STEADY STATE DEG	TURNING RADIUS IN STEADY STATE FT
-4.0	0.397	417.0	13.50	4.3	3288.6
-3.0	0.361	438.0	13.77	3.8	3692.1
-2.0	0.315	465.0	14.06	3.3	4320.6
-1.0	0.253	502.0	14.39	2.6	5499.4
0.	0.160	554.0	14.75	1.6	8900.4
1.0	0.006	585.0	14.98	-0.0	250851.9
2.0	-0.152	567.0	14.77	-1.6	9419.1
3.0	-0.245	531.0	14.41	-2.6	5678.9
4.0	-0.307	486.0	14.07	-3.3	4429.1
5.0	-0.353	454.0	13.77	-3.9	3771.2
6.0	-0.389	429.0	13.49	-4.3	3351.9
7.0	-0.419	409.0	13.24	-4.7	3055.0
8.0	-0.445	393.0	13.01	-5.0	2830.5
9.0	-0.466	378.0	12.80	-5.3	2653.0
10.0	-0.486	365.0	12.59	-5.6	2508.0
15.0	-0.555	500.0	11.72	-6.6	2044.3
20.0	-0.597	452.0	11.02	-7.4	1785.5
25.0	-0.623	415.0	10.41	-8.0	1616.8



PREDICTED TURNING CIRCLE FOR DEG. RUDDER ANGLE



PREDICTED ZIG-ZAG MANEUVER



RATE OF CHANGE OF HEADING VERSUS RUDDER ANGLE FOR PREDICTED SPIRAL MANEUVER

APPENDIX C

FORTRAN LISTING OF COMPUTER PROGRAM

The computer program is coded in the FORTRAN II language available for the IBM 7090 computer at DMB. The FORTRAN listing of the program is included on the following pages. The source program also refers to the subroutines AR PLN1 and AR NXN1 for the least squares curve fitting used in the calculation of the X_u, X_{uu}, and X_{uuu} coefficients and AM PLOT for the Charactron Microfilm Recorder.

The storage required by the program can be greatly reduced in the case the on-line microfilm plotting is left out. A further reduction of program length and storage requirement can be obtained if the calculation of the coefficients X_u, X_{uu}, and X_{uuu} on the basis of EHP-ship data and open-water propeller curves is carried out by a separate program. With these reductions of the program, it should be possible to run the program on any medium-size computer.

The computation time for a prediction of the "Standard Maneuvers" is approximately 6 min on the IBM 7090.

Variables in the program have as far as possible been assigned names that correspond to the established nomenclature. Tables 1-3 give the relationship between the hydrodynamics derivatives in the mathematical model, Equations (10), and the corresponding identifiers in the program.

```
C     PROGRAM XPMC  COMPILED ON IBM 7090 AT DTMB  DECEMBER 1964
C     MANEUVERING CALCULATION NO 1
C     PREDICTION OF STANDARD MANEUVERS FOR SURFACE SHIPS
C
    1 FORMAT (12A6)
    2 FORMAT (1H1,65X5HPAGE ,I2///8X,12A6/)
    3 FORMAT (918)
    4 FORMAT (9F8.2)
    5 FORMAT ( 5P9F8.2)
    6 FORMAT (9F8.5)
    7 FORMAT (1H )
    9 FORMAT (1H-)
      DIMENSION S(2),DTC(9),DZZ(9),DSM(4),DSMD(3),TIT(12)
C     FOLLOWING ARRAYS ARE NECESSARY FOR ON-LINE MICROFILM PLOTTING ONLY
      DIMENSION TA(100),DA(100),PSIA(100),XA(100),YA(100),RA(50)
C     FOLLOVING ARRAYS ARE USEC IN CALC.OF XU,XUU,XUUU ONLY.
      DIMENSION VS(18),EHP(18),ADV(18),CT(18),CQ(18),TH(18),Q(18),
     1RPM(18),XUUD(18),DELVS(18),A(16),P(4),SUM(7)
      INTF(Y1,Y2,Y3,X1,X2,X3,X)=Y2+((Y3-Y2)*(X-X1)/(X3-X2)+(Y2-Y1)*(X3-X
     1)/(X2-X1))*(X-X2)/(X3-X1)
C     THE PROGRAM ALSO REFER TO THE SUBROUTINES AR PLN1,AR NXN1,AM PLOT
C     FOR LEAST SQUARES CURVE FIT  AND CHARACTRON GRAPH PLOT
C
C     INPUT DATA PART I   SPECIFY MANEUVERS TO BE PREDICTED.
      READ 6,DELT,DELR,DELSP,FTSM
C     DELT - TIME INTERVAL IN SOLUTION OF EQUATIONS. DELT=1.0 IS NORMAL.
C     DELR,DELSP - LIMITS SPECIFYING STEADY CONDITION IN SPIRAL.
C                    DELR=.00001,  DELSP=.0001  ARE SUGGESTED.
C     FTSM - MAXIMUM TIME BEFORE NEXT RUDDER DEFLECTION IN SPIRAL.
      LSHIP=1
      LSPEC=1
   30 IF (LSPEC) 49,49,31
   31 READ 3,LTCP,LTC,LZZ,LSM,     GRAPH,LTEST
      IF (GRAPH) 35,35,33
   33 CALL LGCHAR(8,4HXPMC)
B     CHAR1=606060606052
   35 IF (LTCP) 37,37,36
   36 READ 6,DTC1,DTCD,DTC2
   37 IF (LTC) 39,39,38
   38 READ 6,(DTC(J),J=1,LTC)
   39 IF (LZZ) 45,45,40
   40 READ 6,(DZZ(J),J=1,LZZ)
   45 IF (LSM) 49,49,46
   46 READ 6,(DSM(J),J=1,4),(DSMD(J),J=1,3)
C
C     INPUT DATA PART II  SPECIFY PARTICULAR SHIP CHARACTERISTICS.
   49 IF (LSHIP)139,139,50
   50 READ 1,TIT
      READ 3,IMNO,IPNO
      READ 4,ALPP,ALWL,BMLD,DFP,DAP,CG,RAD,DISP,PROP,DIAM,PITCH,AREA,
     1WAKE,TDC,SPEED,RATE,TLAG,TYPE
      READ 3,NEHP,NPC
      READ 4,(VS(J),J=1,NEHP)
      READ 4,(EHP(J),J=1,NEHP)
      READ 6,(ADV(J),J=1,NPC)
      READ 5,(CT(J),J=1,NPC)
      READ 6,(CQ(J),J=1,NPC)
      READ 5,XUDOT,XVV,XRR,XDD,XVR,XVD,XRD,X0
      READ 5,YVDOT,YRDOT,YV,YVVV,YVRR,YVDD,YR,YRRR,YRVV,YRDD,YD,YDDD,
     1YDVV,YDRR,YDU,YVRD,Y0,Y0U
      READ 5,QVDOT,QRDOT,QV,QVVV,QVRR,QVDD,QR,QRRR,QRVV,QRDD,QD,QDDD,
     1QDVV,QDRR,QDU,QVRD,Q0,Q0U
C
C     DIMENSIONAL FACTORS ETC.
      SPF=1.6878
      RTD=57.296
      RHO=1.9905
      HPF  =.001818
  139 U0=SPEED*SPF
C
C     CALCULATION OF COEFFICIENTS XU,XUU,AND XUUU  ON THE BASIS OF SHIP
C     EHP-DATA AND OPEN WATER PROPELLER CURVES.
C
C     I.  INTERPOLATION TO EHP-VALUE AND RESISTANCE AT APPROACH SPEED.
 3050 DO 3070 J=3,NEHP
      IF(VS(J)-SPEED) 3070,3090,3090
 3070 CONTINUE
      J=NEHP
 3090 EHPAS=INTF(EHP(J-2),EHP(J-1),EHP(J),VS(J-2),VS(J-1),VS(J),SPEED)
      RAS=(EHPAS/HPF)/(SPEED*SPF)
C
C     II. ADVANCE COEFF.AT APPROACH SPEED IS FOUND USING REGULA-FALSI
C         METHOD FOR LINEAR ROOT-DETERMINATION
      C1=(SPEED*SPF)*(1.-WAKE)/DIAM
      C2=PROP*RHO*(1.-TDC)*DIAM**4
      C3=C2*C1**2
      C4=C2/(1.-TDC)
      C5=C4*DIAM
      DO 3220 J=1,NPC
      TAS=C3*CT(J)/ADV(J)**2
      YNEW=TAS-RAS
      IF(YNEW) 3240,3220,3220
 3220 YOLD=YNEW
      J=NPC
 3240 DELAD=ADV(J)-ADV(J-1)
      ADVAS=ADV(J)
 3260 DELAD=DELAD*YNEW/(YOLD-YNEW)
      ADVAS=ADVAS+DELAD
      YOLD=YNEW
      CTAS=INTF(CT(J-2),CT(J-1),CT(J),ADV(J-2),ADV(J-1),ADV(J),ADV AS)
      TAS=C3*CTAS/ADVAS**2
      YNEW=TAS-RAS
      IF(.0001*RAS-ABSF(YNEW)) 3260,3260,3330
C
C     III.CALCULATION OF CORRESPONDING PROPELLER RPM,THRUST AND TORQUE.
 3330 RPSAS=C1/ADVAS
      RPMAS=RPSAS*60.
      TAS=C4*CTAS*RPSAS**2
      COAS=INTF(CQ(J-2),CQ(J-1),CQ(J),ADV(J-2),ADV(J-1),ADV(J),ADV AS)
      QAS=C5*COAS*RPSAS**2
C
C     IV. CALC.OF PROP.THRUST,TORQUE,AND RPM AT SPEED-VALUES FOR WHICH
C         EHP IS GIVEN.  CALC.DEPEND UPON TYPE OF MACHINERY SPECIFIED.
      IF (TYPE+5.0) 3420,3570,3570
C         IF (TYPE+5) IS NEGATIV,PROPELLER RPM IS ASSUMED KEPT CONSTANT
 3420 DO 3520 J=1,NEHP
      ADVVS=VS(J)*SPF*(1.-WAKE)/DIAM/RPSAS
      DO 3460 I=3,NPC
```

```
      IF(ADV(I)-ADVVS) 3460,3460,3480
 3460 CONTINUE
      I=NPC
 3480 CTVS=INTF(CT(I-2),CT(I-1),CT(I),ADV(I-2),ADV(I-1),ADV(I),ADVVS)
      CQVS=INTF(CQ(I-2),CQ(I-1),CQ(I),ADV(I-2),ADV(I-1),ADV(I),ADVVS)
      TH(J)=C4*CTVS*RPSAS**2
      Q(J)=C5*CQVS*RPSAS**2
 3520 RPM(J)=RPMAS
      GO TO 3790
C          IF (TYPE+5) IS POSITIV,PROPELLER TORQUE IS ASSUMED TO VARY
C          PROPORTIONAL TO  RPM**TYPE. TYPE=-1.0 FOR A TURBINE ASSUMING
C          CONSTANT POWER (SEMI AUTOMATIC THROTTLE CONTROL).
C          TYPE= 0.0 FOR A DIESEL ENGINE WHICH DELIVER A CONSTANT TORQUE.
 3570 DO 3760 J=1,NEHP
      C6=(VS(J)*SPF)*(1.-WAKE)/DIAM
      C7=C5*C6**2
      DO 3640 I=1,NPC
      QVS=(C7*CQ(I)/ADV(I)**2)*(RPSAS*ADV(I)/C6)**TYPE
      YNEW=QVS-QAS
      IF(YNEW) 3660,3640,3640
 3640 YOLD=YNEW
      I=NPC
 3660 DELAD=ADV(J)-ADV(J-1)
      ADVVS=ADV(J)
 3680 DELAD=DELAD*YNEW/(YOLD-YNEW)
      ADVVS=ADVVS+DELAD
      YOLD=YNEW
      CQVS=INTF(CQ(I-2),CQ(I-1),CQ(I),ADV(I-2),ADV(I-1),ADV(I),ADVVS)
      QVS=(C7*CQVS/ADVVS**2)*(RPSAS*ADVVS/C6)**TYPE
      YNEW=QVS-QAS
      IF(.0001*QAS-ABSF(YNEW)) 3680,3680,3710
 3710 RPSVS=C6/ADVVS
      CTVS=INTF(CT(I-2),CT(I-1),CT(I),ADV(I-2),ADV(I-1),ADV(I),ADVVS)
      TH(J)=C4*CTVS*RPSVS**2
      Q(J)=C5*CQVS*RPSVS**2
 3760 RPM(J)=RPSVS*60.
C
C     V.  X =(PROP.THRUST-RESISTANCE)  IS COMPUTED AT SAME SPEED-VALUES.
 3790 DO 3820 J=1,NEHP
      XUVS=TH(J)*(1.-TDC)-(EHP(J)/HPF)/(VS(J)*SPF)
      XUOD(J)=XUVS   /(RHO*(ALPP*VS(J)*SPF)**2/2.)
 3820 DELVS(J)=(VS(J)-SPEED)/VS(J)
C
C     VI. FAIRING WITH 3RD ORDER POLYNOMIAL OF O-DIM.XU-VALUES AS FUNCT.
C         OF DELVS. GIVING THE COEFFICIENTS XU,XUU,AND XUUU.
      J=3
      I=1
      CALL POLYN (J,NEHP,I,DELVS,XUOD,I,A,P,SUM)
      X0=X0+P(1)
      XU=P(2)
      XUU=P(3)
      XUUU=P(4)
C
C     PRINTING PAGE 1  TABLE OF CONTENTS AND PRINCIPLE SHIP DATA.
      NPAG=1
      PRINT 2,NPAG,TIT
      PRINT170,IMNO,IPNO
  170 FORMAT(1H-, 7X,63HP R E D I C T I O N   O F   S T A N D A R D  M
     1A N E U V E R S////11X13HMODEL NUMBER I8/11X12HPROP. NUMBERI9/////
     2//8X34HT A B L E   O F   C O N T E N T S ///11X58HPRINCIPLE SHIP D
     3ATA (IN CONDITION TESTED) . .     PAGE  1 /11X57HCALCULATION OF CO
     4EFFICIENTS XU,XUU,AND XUUU .     PAGE  2/11X57HCOEFFICIENTS AND ST
     5ABILITY ROOTS  . . . . . .     PAGE  3)
      NPAGI=4
      IF(LTCP)230,230,222
  222 PRINT 223,NPAGI
  223 FORMAT(11X54HTURNING CIRCLE PARAMETERS . . . . . . . . . .      PAG
     1E,I3)
      NPAGI=NPAGI+1
  230 IF(LTC-1)240,231,235
  231 PRINT 232, DTC(1),NPAGI
  232 FORMAT(11X18HTURNING CIRCLE FOR,F6.1,30H DEG. RUDDER  . . . .
     1PAGE,I3)
      GO TO 238
  235 PRINT 236,NPAGI
  236 FORMAT(11X54HPREDICTION OF TURNING CIRCLES . . . . . . . .      PAG
     1E,I3)
  238 NPAGI=NPAGI+LTC*2
  240 IF(LZZ) 250,250,241
  241 PRINT 242,NPAGI
  242 FORMAT(11X54HZIG-ZAG MANEUVER(S) . . . . . . . . . . . .      PAG
     1E,I3)
      NPAGI=NPAGI+LZZ*2
  250 IF(LSM) 270,270,251
  251 PRINT 252,NPAGI
  252 FORMAT(11X54HSPIRAL MANEUVER . . . . . . . . . . . . . .      PAS
     1E,I3)
  270 PRINT 9
      PRINT 276
      PRINT280,ALPP,ALWL,BMLD,EFF,DAP,CG,RAD,DISP,PROP
  276 FORMAT(1H-,7X37HP R I N C I P L E   S H I P   D A T A//)
  280 FORMAT(1H-,10X,                                     47HLENGTH BE
     1TWEEN PERPENDICULARS . . . . . . . . =F7.2,3H FT/11X47HLENGTH ON W
     2ATER LINE  . . . . . . . . . . . . =F7.2,3H FT//11X47HMOULDED BEAM
     3  . . . . . . . . . . . . . . . . =F7.2,3H FT/11X47HDRAFT AT F.P.
     4. . . . . . . . . . . . . . . . =F7.2,3H FT/11X47HDRAFT AT A.P. .
     5. . . . . . . . . . . . . . . =F7.2,3H FT/11X47HL.C.G.  . . . . .
     6. . . . . . . . . . . . . . . =F7.2,3H FT/11X47HRADIUS OF GYRATION
     7. . . . . . . . . . . . . =F7.2,3H FT/11X47HDISPLACEMENT  . . . .
     8. . . . . . . . . . . . . =F7.0,5H TONS//11X47HNUMBER OF PROPELLERS
     9 . . . . . . . . . . . . . =F6.1)
      PRINT 390,DIAM,PITCH,AREA,RPMAS,SPEED,RATE,TLAG
  390 FORMAT(11X47HPROPELLER DIAMETER  . . . . . . . . . . . . . =F7.2,3
     1H FT/  11X47HPITCH RATIO AT 0.7 R  . . . . . . . . . . . =F7.2/1
     21X47HPROJ. AREA / DISC AREA  . . . . . . . . . . . =F7.2/11X47HREV
     3OLUTIONS . . . . . . . . . . . . . . . . . =F6.1,5H  RPM//11X47HAP
     4PROACH SPEED  . . . . . . . . . . . . . . =F7.2,6H KNOTS/11X47HR
     5UDDER RATE . . . . . . . . . . . . . . . . =F7.2,8H DEG/SEC/11X4
     67HTIME LAG OF RUDDER SYSTEM . . . . . . . . . . =F7.2,4H SEC)
C
C     PRINTING OF PAGE 2  GIVING CALCULATION OF COEFF. XU,XUU,AND XUUU.
      NPAG=NPAG+1
      PRINT 2,NPAG,TIT
      PRINT 4040,SPEED,WAKE,TDC
 4040 FORMAT(1H-, 7X,59HCALCULATION OF THE NON-DIM. COEFFICIENTS  XU, XU
     1U, AND XUUU/8X,61HON THE BASIS OF SHIP EHP-DATA AND OPEN-WATER PRO
     2PELLER CURVES///11X,45HX-FORCE = PROPELLER THRUST*(1-T) - RESISTAN
     3CE/13X,50H= XU*DELU + XUU*DELU**2 + XUUU*DELU**3   (NON-DIM)/11X,5
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      49H*HERE      DELU = (U-U0)/U = NON-DIM.CHANGE IN FORWARD SPEED//8X,
     517HX IS COMPUTED FOR/11X,14HAPPROACH SPEED,26X4HU0 =,F7.2,6H KNOTS
     6/11X,16HWAKE COEFFICIENT,24X4HW  =,F8.3/11X,28HTHRUST DEDUCTION CO
     7EFFICIENT,12X4HT  =,F8.3)
      IF(TYPE+5.0) 4130,4165,4165
 4130 PRINT 4140
 4140 FORMAT(11X,55HPROPELLER REVOLUTIONS KEPT CONSTANT DURING THE MANEU
     1VER)
      GO TO 4240
 4165 IF (TYPE) 4210,4170,4210
 4170 PRINT 4180
 4180 FORMAT(11X,11HDIESEL SHIP/11X,50HPROPELLER TORQUE KEPT CONSTANT DU
     1RING THE MANEUVRE)
      GO TO 4240
 4210 PRINT 4220,TYPE
 4220 FORMAT(11X,52HTURBINE SHIP - PROPELLER TORQUE VARY PROPORTIONAL TO
     1/26X,14HREVOLUTIONS INF7.3,22H POWER DURING MANEUVRE)
 4240 PRINT 4250
 4250 FORMAT(1H0, 7X,50HOPEN WATER PROPELLER CHARACTERISTICS  (INPUT DAT
     1A)/11X,25HADVANCE   THRUST   TORQUE/11X,25HCOEFF.     COEFF.   COEF
     2F./13X,21HJ          KT        KQ//)
      PRINT 4290,(ADV(J),CT(J),CQ(J),J=1,NPC)
 4290 FORMAT(F17.3,F9.3,F10.4)
      PRINT 4310
 4310 FORMAT(1H0,7X,26HEHP-INPUT-DATA   PROPELLER/75H   SPEED  EHP   RES
     1IST.  THRUST TORQUE  REVS.    X      DELU     X    X*10+5/16X, 21H*
     210-5     *10-5  *10-5,10X5H*10-5,10X13H*10+5  FAIRED/74H   KNOTS
     3       LB        LB   LB*FT     RPM     LB    0-DIM  0-DIM  0-DIM//)
      PRINT4360,SPEED,EHPAS,RAS,TAS,QAS,RPMAS
      PRINT 7
 4360 FORMAT(F7.1,F7.0,-5PF8.4,F9.4,F7.4,0PF6.1,-5PF9.4,0PF7.3,5PF8.2,F7
     2.2)
      DO 4430 J=1,NEHP
      XFAIR=(( XUUU*DELVS(J)+XUU)*DELVS(J)+XU)*DELVS(J) +P(1)
      RVS=(EHP(J)/HPF)/(VS(J)*SPF)
      XUVS=TH(J)*(1.-TDC)-RVS
      PRINT 4360,VS(J),EHP(J),RVS,TH(J),Q(J),RPM(J),XUVS,DELVS(J),
     1XUOD(J),XFAIR
 4430 CONTINUE
      PRINT 4450,XU,XUU,XUUU
 4450 FORMAT(1H0,7X,22HCOEFFICIENTS (NON-DIM)/11X,6HXU   =5P1F9.1,3HE-5/
     111X,6HXUU  =F9.1,3HE-5/11X,6HXUUU =F9.1,3HE-5)
C
C     PRINTING PAGE 3 GIVING HYDRODYNAMIC COEFFICIENTS.
      NPAG=NPAG+1
      PRINT 2,NPAG,TIT
      PRINT 7
      PRINT 460,XUDOT,YVDOT,QVDOT,YRDOT,QRDOT,XU,YV,QV
  460 FORMAT(8X38HC O E F F I C I E N T S   (INPUT DATA)///8X43HTHE FOLL
     1OWING COEFFICIENTS OF THE EQUATIONS/ 8X46HOF MOTION ARE DESCRIBED
     2IN DTMB REPORT NO.XXXX//74H   X - E Q U A T I O N      Y - E Q U
     3A T I O N       N - E Q U A T I O N//73H    VAR-       COEFF-
     4    VAR-        COEFF-              VAR-       COEFF- /72H    IABLE      I
     5CIENT              IABLE      ICIENT              IABLE     ICIENT//10H
     6X UDOT5PF9 1,17HE-5          Y VDOTF9.1,18HE-5          N VDOT F8.1,3H
     7E-5/37H                               Y RDOT F8.1,18HE-5          N R
     8DOT F8.1,3HE-5//11H    X U     F8.1,18HE-5          Y V     F8.1,18HE-
     95          N V     F8.1,3HE-5)
      PRINT 580,XUU,YVVV,QVVV,XUUU,YVRR,QVRR,XVV,YVDD,QVDD,XRR,YR,QR,XDD
     1,YRRR,QRRR,XVR,YRVV,QRVV,XVD,YRDD,QRDD,XRD,YD,QD
  580 FORMAT(9H    X UU 5PF10.1,18HE-5          Y VVV  F8.1,18HE-5
     1N VVV  F8.1,3HE-5/11H    X UUU  F8.1,18HE-5           Y VRR  F8.1,18H
     2E-5          N VRR  F8.1,3HE-5/11H    X VV   F8.1,18HE-5          Y VD
     3D  F8.1,18HE-5          N VDD  F8.1,3HE-5/11H    X --   F8.1,18HE-5
     4          Y R    F8.1,18HE-5          N R    F8.1,3HE-5/11H    X DD   F
     58.1,18HE-5          Y RRR  F8.1,18HE-5          N RRR  F8.1,3HE-5/11H
     6    X VR   F8.1,18HE-5          Y RVV  F8.1,18HE-5          N RVV  F8.1
     7,3HE-5/11H    X VD   F8.1,18HE-5          Y RDD  F8.1,18HE-5
     8N RDD  F8.1,3HE-5/11H    X RD   F8.1,18HE-5          Y D    F8.1,18H
     9E-5          N D    F8.1,3HE-5)
      PRINT 690,YDDD,QDDD,YDVV,QDVV,YDRR,QDRR,YDU,QDU,YVRD,QVRD,X0,Y0,Q0
     1,YUU,QUU
  690 FORMAT(35H                               Y DDD5PF10.1,17HE-5
     1 N DDD F9.1,3HE-5/37H                               Y DVV  F8.1,18H
     2E-5          N DVV  F8.1,3HE-5/37H                               Y DR
     3R  F8.1,18HE-5          N DRR  F8.1,3HE-5/37H
     4          Y DU   F8.1,18HE-5          N DU   F8.1,3HE-5/37H
     5                    Y VRD  F8.1,18HE-5          N VRD  F8.1,3HE-5/11H
     6    X 0    F8.1,18HE-5          Y 0    F8.1,18HE-5          N 0    F8.1
     7,3HE-5/37H                               Y OU   F8.1,18HE-5
     8N UU   F8.1,3HE-5///70H    UNITS OF MASS          = LB*SEC**2/FT
     9  0-DIM.WITH  RHO*LPP**3/2 )
      PRINT 770
  770 FORMAT(12X62HX AND Y FORCES = LB               -  -  -   RHO*LPP*
     1*2*U**2/2/12X62HN MOMENT          = LB*FT           -  -  -   RHO*L
     2PP**3*U**2/2/12X48HU AND V          = FT/SEC         -  -  -   U
     3 /12X       52HR              = RADIANS/SEC      -  -  -   U/LPP
     4/12X       24HD              - RADIANS/12X     55HUDOT AND VDOT  =
     5 FT/SEC/SEC       -  -  -  U**2/LPP  /12X      58HROOT
     6 = RADIANS/SEC/SEC   -  -  -   U**2/LPP**2  ////)
C
C     CALCULATION OF 0-DIM. STABILITY ROOTS
      DET= YVDOT*QRDOT-YRDOT*QVDOT
      B= QVDOT*YR+YRDOT*QV-QRDOT*YV-YVDOT*QR
      C= YV*QR-QV*YR
      SIG1= (-B+SQRTF(B*B-4.*DET*C))/DET/2.
      SIG2= (-B-SQRTF(B*B-4.*DET*C))/DET/2.
      SIG3= XU/XUDOT
      SLOPE=    -(YV*QD-QV*YD)/C*U0/ALPP
      PRINT1040,SIG1,SIG2,SIG3,C,SLOPE
 1040 FORMAT(7X24HS T A B I L I T Y   R O O T S//12X10HSIGMA 1  =E12.4/1
     12X10HSIGMA 2  =E12.4/12X10HSIGMA 3  =E12.4//7X24HSTABILITY CRITERI
     2ON =E12.4 /7X21HSLOPE OF R-D CURVE  =E12.4,14H (DEG/SEC)/DEG)
C
C     CALC. OF INITIAL RUD. ANGLE FOR SHIP SAILING STRAIGHT AHEAD.
      DRIN=(QVDOT*Y0-YVDOT*Q0)/(YVDOT*QD-QVDOT*YD)
      DIN= DRIN*RTD
C
C     GENERAL PROGRAM
      S(1)=1.0
      S(2)=-1.0
C
C     CALCULATION OF TURNING CIRCLE PARAMETERS
      IF (LTCP) 1370,1370,1140
 1140 M1=2
      NPAG=NPAG+1
      PRINT 2,NPAG,TIT
      PRINT 1180
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1180 FORMAT(1H-,7X49HT U R N I N G   C I R C L E   P A R A M E T E R S/
    175H- RUD  ADVANCE  TRANS-   MAX   TACT  TIME FOR    MAX  STEADY ST
    2EADY  FINAL /74H ANGLE (90 DEG)  FER   ADVANCE DIAM  HDG CHANGE TR
    3ANS- TURN  DRIFT   SPEED/75X 8H(90 DEG),14X29H(90) (180)  FER   RA
    4D   ANGLE/        74H  DEG      FT        FT      FT      FT     SEC  SE
    5C     FT     FT     DEG     KNOTS////)
     J1=0
     MS=1
1260 DF=(DTC1+FLOATF(J1)*DTCD)*S(MS)
     GO TO 5020
1280 PRINT 1290,D,NX90,NY90,NXMA,NTDIA,NT90,NT180,NYMT,RAD,DRIFT,FINSP
1290 FORMAT(F6.1,17,18,17,17,16,15,17,F7.0,F6.1,F8.2)
     MS=3-MS
     IF(MS-2) 1320,1260,1260
1320 PRINT 7
     J1=J1+1
     IF (DTC2+DF) 1370,1370,1260
C
C    CALCULATION OF TURNING CIRCLE FOR SPECIFIED RUDDER DEFLECTION
1370 IF (LTC) 1790,1790,1380
1380 M1=3
     DO 1770 J1=1,LTC
     DF=DTC(J1)
     MS=1
     IF (DF) 1430,1790,1440
1430 MS=2
1440 NPAG=NPAG+1
     PRINT 2,NPAG,TIT
     PRINT 1470,DF
     PRINT 9
     PRINT 1480
1470 FORMAT(1H-, 7X,35HT U R N I N G   C I R C L E   F O RF5.1,20H D E
    1G . R U D D E R)
1472 FORMAT(1H ,32X,11H(CONTINUED)///)
1480 FORMAT(73H    TIME     RUDDER   ADVANCE  TRANS-    SPEED   HEADING
    1 ANGULAR   DRIFT/18H     AFTER     ANGLE,14X3HFER,14X25HANGLE     VE
    2LOCITY  ANGLE /11H     EXECUTE/72H      SEC       DEG         FT
    3FT      KNOTS      DEG      DEG/SEC     DEG///)
     GO TO 5020
C    PREPARATION OF DATA FOR CHARACTRON PLOT OF TURNING CIRCLE
1540 IF (GRAPH) 1770,1770,1550
1550 DO 1580 J3=1,50
     RX2=200.*FLOATF(J3)
     IF(RX2-XMA)1580,1590,1590
1580 CONTINUE
1590 DO 1620 J4=1,50
     RX1=-200.*FLOATF(J4)
     IF(RX1+(RAD*2.-XMA))1630,1630,1620
1620 CONTINUE
1630 I1=J3+J4
     DO 1670 J3=1,50
     RY2=FLOATF(J3)*200.
     IF(RY2-ABSF(YMT)) 1670,1680,1680
1670 CONTINUE
1680 RY1=-200.
     I3=J3+1
     IF(YMT) 1710,1730,1730
1710 RY1= RY2
     RY2=200.
1730 CALL FNPLOT(62H(57H    PREDICTED TURNING CIRCLE FOR       DEG. RUDDE
    1R ANGLE    ),23H(18H  TRANSFER  IN FT ),22H(17H  ADVANCE  IN FT ),
    2RY1,RY2,RX1,RX2,I3,1,I1,1,6H(F5.0),6H(F5.0))
     CALL CURVE (YA(K1),XA(K1),K1,6H       )
1770 CONTINUE
C
C    CALCULATION OF ZIG-ZAG MANEUVER
1790 IF (LZZ) 2010,2010,1800
1800 M1=4
     DO 1990 J1=1,LZZ
     DF=-ABSF(DZZ(J1))
     MS=2
     NPAG=NPAG+1
     PRINT 2,NPAG,TIT
     PRINT 1870,DF,DF
     PRINT 9
     PRINT 1480
1870 FORMAT(1H-,7X,F4.1,11H D E G . - ,F4.1,40H D E G . Z I G - Z A G
    1 M A N E U V E R)
     GO TO 5020
1930 IF (GRAPH) 1990,1990,1940
1940 CALL FNPLOT(36H(31H    PREDICTED ZIG-ZAG MANEUVER  ),41H(36H  TIME
    1FROM INITIAL EXECUTE   IN SEC ),48H(43H  HEADING ANGLE  AND  RUDDER
    2 ANGLE   IN DEG ),0.,420.,-40.,40.,7,1,8,1,6H(F6.1),6H(F3.0))
     CALL CURVE (TA(43),PSIA(43),43,6H       ),
     CALL CURVE (TA(43),DA(43),43,6H      *)
1990 CONTINUE
C
C    CALCULATION OF SPIRAL MANEUVER
2010 IF(LSM) 2340,2340,2020
2020 M1=1
     NPAG=NPAG+1
     PRINT 2,NPAG,TIT
     PRINT 2060
     PRINT 2070
2060 FORMAT(1H-, 7X,29HS P I R A L   M A N E U V E R////)
2065 FORMAT(1H-, 7X,43HS P I R A L   M A N E U V E R   (CONTINUED)////)
2070 FORMAT(71H     RUDDER        STEADY        TIME TO       SPEED        DRIF
    1T          TURNING/73H      ANGLE          RATE OF        REACH         IN
    2       ANGLE IN      RADIUS IN/16X54HCHANGE OF    STEADY         STEADY
    3    STEADY        STEADY/16X53HHEADING        STATE          STATE        ST
    4ATE          STATE/68H        DEG          DEG/SEC         SEC           KNOTS
    5          DEG               FT///)
     MS=2
     J1=1
     J2=1
     J4=1
     DF=DSM(J1)
     D=DF
     GO TO 5040
2160 PRINT 2170,D,RDIM,T,FINSP,DRIFT,RAD
2170 FORMAT(F8.1,F14.3,F11.1,F12.2,F12.1,F13.1)
     IF(J2-5*J4)2180,2172,2180
2172 PRINT 7
     J4=J4+1
     IF(J2-35)2180,2176,2180
2176 NPAG=NPAG+1
     PRINT 2,NPAG,TIT
     PRINT 2065
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      PRINT 2070
 2180 J3=J1-1+MS
      IF((DF-DSM(J3))*S(MS))2240,2200,2200
 2200 J1=2*MS-3+J1
      IF (J1) 2270,2270,2215
 2215 IF (J1-3)2240,2240,2220
 2220 MS-1
      J1=3
 2240 DA(J2)=D
      RA(J2)=RDIM
      DF=DF+DSMD(J1)*S(MS)
      J2=J2+1
      GO TO 5060
 2270 IF (GRAPH) 9010,9010,2280
 2280 CALL FNPLOT(82H(77H  RATE OF CHANGE OF HEADING VERSUS RUDDER ANGLE
     1 FOR PREDICTED SPIRAL MANEUVER),68H(63H  STARBOARD              RUDDE
     2R ANGLE    IN DEG                    PORT),63H(58H  STEADY RATE OF CHAN
     3GE OF HEADING   IN DEGREES PER SECOND),-25.,25.,-1.0,1.0,10,1,10,1
     4,6H(F3.0),6H(F4.1))
      CALL CURVE (DA(J2),RA(J2),J2,CHART)
C
 2340 GO TO 9010
C
C     CONTINUOUS TIME BASE SOLUTIONS OF DIFFERENTIAL EQUATIONS GOVERNING
C     SHIP MOTION IN THE HORIZONTAL PLANE.
 5020 D=DIN
      FINSP=SPEED
      J4=1
 5040 ERASE DELU,V,R,PSI,XDIM,YDIM,VDIM,RDIM,DRIFT
      UDIM=UC
 5060 MTC=1
      TSRM=0.
      DO 5730 K1=1,70
      T1=DELT*10.*FLOATF(K1-1)
      IF(M1-3)5180,5110,5110
 5110 PRINT 5120,T1,D,XDIM,YDIM,FINSP,PSI,RDIM,DRIFT
 5120 FORMAT(2F9.1,F10.1,F9.1,F8.2,F9.1,F10.3,F8.1)
      IF (K1  -5*J4)5135,5122,5135
 5122 PRINT 7
      J4=J4+1
      IF (K1  -35)5135,5125,5135
 5125 NPAG=NPAG+1
      PRINT 2,NPAG,TIT
      IF (M1-3)5135,5128,5130
 5128 PRINT 1470,DF
      GO TO 5131
 5130 PRINT 1870,DF,DF
 5131 PRINT 1472
      PRINT 1480
 5135 XA(K1)=XDIM
      YA(K1)=YDIM
      TA(K1)=T1
      PSIA(K1)=PSI
      DA(K1)=D
 5180 DO 5730 K2=1,10
      T=T1+DELT*FLOATF(K2)
      IF(MTC-1)5210,5210,5280
 5210 IF(T-TSRM-TLAG)5280,5280,5220
 5220 D=D+DELT*RATE*S(MS)
      IF((D-DF)*S(MS)) 5280,5240,5240
 5240 D=DF
      MTC=2
      IF(M1-3)5275,5275,5270
 5270 MTC=8
 5275 IF (M1-1) 5280,5276,5280
 5276 MTC=6
 5280 DR=D/RTD
      XBAR=((XUUU*DELU+XUU)*DELU+XU)*DELU+XVV*V*V+XRR*R*R+XDD*DR*DR+XVR*
     1V*R+XVD*V*DR+XRD*R*DR+X0
      YBAR=(YV+YVVV*V*V+YVRR*R*R+YVDD*DR*DR)*V+(YR+YRRR*R*R+YRVV*V*V+YRD
     1D*DR*DR)*R+(YD+YDDD*DR*DR+YDVV*V*V+YDRR*R*R+YDU*DELU)*DR+YVRD*V*R*
     2DR+Y0+Y0U*DELU
      QBAR=(QV+QVVV*V*V+QVRR*R*R+QVDD*DR*DR)*V+(QR+QRRR*R*R+QRVV*V*V+QRD
     1D*DR*DR)*R+(QD+QDDD*DR*DR+QDVV*V*V+QDRR*R*R+QDU*DELU)*DR+QVRD*V*R*
     2DR+Q0+Q0U*DELU
      UDOT=XBAR/XUDOT
      VDOT=(QRDOT*YBAR-YRDOT*QBAR)/DET
      RDOT=(YVDOT*QBAR-QVDOT*YBAR)/DET
      ACC=UDIM*UDIM/ALPP
      UDIM=UDIM+UDOT*DELT*ACC
      VDIM=VDIM+VDOT*DELT*ACC
      RDIM=RDIM+RDOT*DELT*ACC/ALPP*RTD
      DELU=(UDIM-U0)/UDIM
      V=VDIM/UDIM
      R=RDIM*ALPP/UDIM/RTD
      PSI=PSI+RDIM*DELT
      DELY=DELT*(V*COSDF(PSI)+SINDF(PSI))*UDIM
      DELX=DELT*(COSDF(PSI)-V*SINDF(PSI))*UDIM
      YDIM=YDIM+DELY
      XDIM=XDIM+DELX
      FINSP=SQRTF(UDIM*UDIM+VDIM*VDIM)/SPF
      RAD=FINSP*SPF/ABSF(RDIM)*RTD
      DRIFT=-ATANF(V)*RTD
      GO TO(5730,5570,5620,5650,5690,5720,5725,5510),MTC
 5510 IF((-PSI-DF)*S(MS)) 5730,5520-5520
 5520 DF=-1.*DF
      MS=3-MS
      MTC=1
      TSRM=T
      IF(K1-51)5730,5740,5740
 5570 IF(ABSF(PSI)-90.)5730,5580,5580
 5580 NX90=XDIM
      NY90=YDIM
      NT90=T
      MTC=3
 5620 IF(DELX)5630,5630,5730
 5630 NXMA=XDIM
      XMA=XDIM
      MTC=4
 5650 IF(ABSF(PSI)-180.)5730,5660,5660
 5660 NTDIA=ABSF(YDIM)
      NT180=T
      MTC=5
 5690 IF(YDIM*DELY)5700,5700,5730
 5700 NYMT=YDIM
      YMT=YDIM
      MTC=6+(2*M1)/5
 5720 ARDOT=(ABSF(YVDOT*QBAR)+ABSF(QVDOT*YBAR))/DET*DELT*ACC*RTD/ALPP
```

```
      AUDOT=ABSF(UDOT)*DELT*ACC/SPF
      IF (AUDOT-DELSP) 5721,5721,5722
 5721 IF (ARDOT-DELR)  5740,5740,5722
 5722 IF(T-FTSM) 5730,5730,5740
 5725 IF(ABSF(PSI)-450.)5730,5730,5740
 5730 CONTINUE
 5740 GO TO (2160,1280,1540,1930),M1
C
C     TEST ON LTEST IF NEW SET OF DATA SHOULD BE READ.
 9010 IF(LTEST)9020,9050,30
 9020 READ 4,SPEED
 9030 READ 3,LTEST,LSPEC,LSHIP
      GO TO 30
 9050 PRINT 9060
 9060 FORMAT(40H1END JOB REACHED THROUGH PROGRAM CONTROL)
      IF(GRAPH)9100,9100,9080
 9080 CALL LGCHAR(8,4HXPMC)
      END FILE 8
 9100 CALL END JOB
      END
```

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) David Taylor Model Basin Department of the Navy Washington, D. C.	2a. REPORT SECURITY CLASSIFICATION Unclassified	
	2b GROUP	
3 REPORT TITLE A DIGITAL COMPUTER TECHNIQUE FOR PREDICTION OF STANDARD MANEUVERS OF SURFACE SHIPS		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5 AUTHOR(S) (Last name, first name, initial) Strom-Tejsen, Jorgen		
6 REPORT DATE December 1965	7a. TOTAL NO OF PAGES 87	7b. NO OF REFS 6
8a. CONTRACT OR GRANT NO. b. PROJECT NO c d.	9a. ORIGINATOR'S REPORT NUMBER(S) 2130 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10 AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited		
11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Bureau of Ships Washington, D. C.	

13 ABSTRACT

This report presents a computer program for the solution of a mathematical model representing the motion of a surface ship, giving predictions of steering and maneuvering qualities. The nonlinear mathematical model based on a third-order Taylor expansion of forces and moments in the equations of motion is reviewed. The hydrodynamic derivatives representing the input to the program can be obtained from present captive model testing techniques. Any motion of a surface ship including tight maneuvers and loop phenomenon recognized in the spiral maneuver for a directional unstable ship should be predictable with accuracy. The computer program which gives predictions for the "Standard Maneuvers," turning circles, zig-zag, and spiral maneuver, is described, and results of sample calculations are included. An instruction for preparation of input data for the program, samples of the computer results, and the FORTRAN listing of the computer program are also given.

DD FORM 1 JAN 64 1473

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